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ALUMINUM COMPANY OF AMERICA
Alcoa Research Laboratories
Chemical Metallurgy Division
New Kensington, Pennsylvania

INVESTIGATION OF THE STRESS-CORROSION CRACKING OF HIGH STRENGTH ALUMINUM ALLOYS

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Summary Report

(Period of May 6, 1963, to July 6, 1965)

D. O. Sprowls, Project Supervisor

Authors:

B. W. Lifka
W. King
M. B. Shumaker
R. A. Kelsey
D. G. Vandenburgh

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SYNOPSIS:

Research and Development Contract NAS 8-5340, between the Aluminum Company of America and the National Aeronautics and Space Administration, has completed two years' duration for Phases I, II and III and one year for Phase IV. The results of the work performed in these four distinct phases are as follows:

Phase I - Stress Corrosion Tests of Various Alloys in Several Environments

Stress corrosion tests were performed on transverse specimens from 2.5" diameter rolled rod of eleven different alloys and tempers selected to give a range of performance. Alloys 7075-T7351, 2219-T87, -T851, -T62 and 2024-T851 have demonstrated the expected freedom from stress-corrosion cracking at the relatively high applied stress of 75% of the yield strength. Stress-corrosion cracking occurred in alloys 2024-T351, 2014-T651, X7006-T651, 7079-T651 and 7178-T651 when the sustained tensile stress exceeded 25% of the yield strength. Specimen life was considerably shorter in the 3.5% NaCl alternate immersion environment than in the outdoor atmospheric environments, but the probability of failure in the atmospheres was as great as or even greater for certain alloys at low stress levels. An acidified intermittent salt spray test shows promise as a test requiring shorter exposure periods than the 3.5% NaCl alternate immersion test and more closely duplicating the threshold values established in the atmosphere for aluminum alloys of all types.

Phase II - Evaluation of Surface Treatments and Protective Coatings to Prevent Stress-Corrosion Cracking

On the basis of a literature survey, fourteen protective methods were selected, applied to four different aluminum alloys (2014-T651, 2024-T351, 7079-T651 and 7178-T651) in the form of interference-stressed rings and exposed to several environments.

While only one of the protective treatments has to date been capable of preventing stress-corrosion cracking, several appear able to extend the useful life of susceptible alloys for significant periods. The best protection was obtained with a combination of either shot peening or metallized 7072 alloy plus an epoxy-polyamide paint system. Separate treatments, such as metallized 7072, zinc electroplate or an epoxy-polyamide paint system, are also of merit; however, anodic films such as Alumilite 205 and 226 were not effective in preventing stress-corrosion cracking.

Phase III - Development of Rapid Criteria for Stress Corrosion Resistant Tempers of 2219 Alloy Products

The development of aluminum alloys and tempers such as 2219-T851, 2219-T87 and 7075-T73, with a high order of resistance to stress-corrosion cracking, has resulted in a need for faster tests to establish the performance of these materials. Ten electrolytes were investigated in an effort to obtain a cracking medium more aggressive than sodium chloride solutions for 2219 alloy. Two of the electrolytes (aqueous solutions of NaCl, CrO_3 and $K_2Cr_2O_7$) appear sufficiently promising to justify further investigation.

A solution potential technique for predicting the stress corrosion performance of 2219 alloy products has been developed. Measurements are made in an organic electrolyte consisting of a mixture of carbon tetrachloride and methyl alcohol. This technique is very sensitive for the cold worked -T851 and -T87 tempers, but not for the unworked -T6 and -T62 tempers. Consequently, further work is required before they can be used to evaluate the stress corrosion performance of the latter tempers.

Phase IV - Stress Corrosion Tests of Weldments of Al-Zn-Mg Alloys

Stress corrosion tests were performed on welded joints of four relatively new high strength weldable aluminum alloys, i.e. X7002, X7106, 7039 and X7139, loaded by different methods (bending and tension) and exposed to several environments to compare the alloys and to establish the best test procedure. The majority of the welds were made in 1/8" thick sheet and 3/8" thick plate (also 1" thick plate for X7106-T6351) by the Direct Current Straight Polarity Tungsten-Inert-Gas (DCSP-TIG) process with X5180 filler wire. Limited tests were also made with the Direct Current Reverse Polarity Metal-Inert-Gas (DCRP-MIG) process (X7106-T6351) and with 5183 filler (7039-T6, -T651). The welds were tested in both the as-welded and post-weld aged (8 hours at 225°F + 16 hours at 300°F) conditions.

The general resistance to corrosion of the parent Al-Zn-Mg alloys was good; but in the as-welded condition, all four alloys suffered severe localized corrosion of the heat affected zone. This attack was greatly diminished by post-weld aging (8 hours at 225°F + 16 hours at 300°F).

Preliminary results of the stress corrosion tests indicated very good resistance to stress-corrosion cracking of all four alloys when welded and stressed either in bending or tension as high as 75% of their weldment yield strength. While post-weld aging increased the weld strength and decreased the localized corrosion at the heat affected zone, the resistance to stress-corrosion cracking was markedly decreased. Both X7106 and X7139 welded with X5180 showed equally poor resistance after aging, 7039 welded with 5183 being most resistant, and X7002 welded with X5180 being intermediate.

Plate to forging combinations of X7106 alloy with different grain orientations showed the same resistance to stress-corrosion cracking as the plate. Painting these combinations increased their times to failure but did not prevent cracking.

Direct tension loading, either in a constant load (spring) or constant deformation type of fixture, caused more rapid failureof susceptible materials than bending in constant deformation fixtures. Both methods of tension loading, however, also caused in severely corroded (as-welded) specimens long time failures that are currently being diagnosed. Further work is required to evaluate these test methods.

SCOPE:

The increasing complexity of aerospace design and a need to utilize the greatest strength-to-weight ratio possible have caused stress corrosion failures to become an increasing problem in recent years. "Failures of high strength aluminum and steel aircraft components from stress-corrosion cracking have been numerous, expensive and in many cases spectacular. Every modern weapons system flying has had at least one stress corrosion failure of a major component which has cost many dollars in repairs and downtime."(1) Service failures of aluminum alloys have almost invariably resulted from residual or assembly surface* transverse direction relative to the grain structure. For cases where sustained tension stressed in the short transverse direction cannot be avoided by design, it is necessary to select the most stress corrosion resistant alloys and tempers; when this, too, is impossible, it becomes very important to know the capability of surface treatments and protective coatings.

In order for materials engineers and designers to learn the stress corrosion characteristics of commercial alloys, including newly developed products, it is necessary that reliable stress corrosion test methods be available to develop stress corrosion data. Accelerated tests can be very helpful, but they can be worse than no test if they only serve to "give the wrong answer faster." Thus, in the selection of test procedures, care must be taken to choose specimens, loading methods and test environments

*tension stresses acting continuously in the short that will produce the mode of failure and the relative ratings of materials that are consistent with differences in serviceability. Therefore, the following objectives were undertaken in this investigation:

1. Investigate the resistance to stress-corrosion cracking of the several types of high strength aluminum alloys in various natural environments and laboratory test media.

2. Evaluate the feasibility of preventing stress-corrosion cracking of susceptible alloys by the use of various protective surface treatments and coatings selected after a survey of pertinent literature.

3. Develop rapid criteria for proving the high resistance to stress-corrosion cracking of properly heat treated 2219 alloy products.

4. Determine the resistance to stress-corrosion cracking of welded joints of the relatively new commercial alloys of the Al-Zn-Mg type.

5. Compare stress corrosion test data obtained on welded joints loaded by different methods to establish the best test procedure.

EXPERIMENTAL PROCEDURE AND RESULTS

Phase I

Stress Corrosion Tests of Various Alloys in Several Environments

OBJECT:

The objective of this first portion of the contract was to investigate the stress corrosion behavior of a wide range of commercial high strength, heat treatable aluminum alloys and tempers in various outdoor atmospheres and laboratory tests. This served a dual purpose of comparing newer alloys or tempers with older ones, more familiar to the general industry, and of furnishing a reference datum for subsequent evaluations of protective treatments in Phase II.

MATERIAL:

The material evaluated was mill fabricated 2 1/2" diameter rolled rod of the alloys and tempers shown in Table I. All were 100 per cent ultrasonically inspected and had chemical compositions and mechanical properties that met specifications (Table I).

PROCEDURE:

The specimen employed was an 1/8" diameter tensile bar machined in the transverse direction as shown in Figure 1 (a). These were stressed in direct tension by means of ARL's stressing frame to various percentages of the yield strength. The strain placed upon each specimen was measured while the load was applied by pressure on the side bars of the frame. Specimens were exposed to 3.5% NaCl alternate immersion (one-hour cycle with ten-minute immersion followed by fifty-minute drying in air at ambient room temperature) for twelve weeks and to three natural environments (New Kensington, Pennsylvania, industrial atmosphere and Point Comfort, Texas, and Point Judith, Rhode Island, seacoast atmospheres) for a tentative two-year period. All eleven items were exposed to alternate immersion but only the six alloys indicated by footnote 6 in Table I were exposed to atmospheres. A group of specimens mounted on an atmospheric exposure rack is shown in Figure 2. Representative failures were examined microscopically to verify the nature of failure. An example of the type of evidence required to conclusively indicate stress-corrosion cracking as the mechanism of failure is given in Figure 3.

EXPERIMENTAL RESULTS:

The tests in alternate immersion were completed during the first year of the contract and the detailed stress corrosion data for this environment are contained in Table IV of the first year summary report.(2) The atmospheric tests have completed eighteen to twenty months of exposure and the detailed data obtained are given in Table II of this report. A graphical comparison of the various environments is made in Figures 4 and 5, respectively, as regards the "threshold stress" level and the specimen lives.

Interpretation of the data contained in the above tables and figures must be tempered by the fact that the tests, while quite extensive, were limited to a single lot of each item.

A. Comparison of the Alloys and the Effect of the Various Environments on the Basis of the "Threshold Stress" Below Which Failure Was Not Encountered

Probably the most striking observation illustrated by the data is the excellent resistance afforded by alloys 2219-T87 and 7075-T7351 in all environments. A very low probability of failure, approaching 0%, is expected of these alloys even at sustained transverse tension stresses as high as 75%Y.S. This excellent performance has been verified by Alcoa on numerous commercial lots of various products.

The other four alloys, in general, performed similarly to one another, with "threshold stresses" of about 25% of the actual transverse yield strength (approximately 15 ksi)(Figure 4). These data agreed well with "threshold" established previously for these alloys.(3)

In these particular tests the alternate immersion environment was less severe than the atmospheres except in the case of the 2014-T651 specimens exposed at New Kensington, Pennsylvania (Figure 4). There are sufficient other data to indicate that this is a real effect for alloys 7079-T651 and X7006-T651. However, as regards 2014-T651, 7178-T651 and most other alloys, the general experience has been that alternate immersion is equally as severe as seacoast atmospheres and more severe than industrial atmospheres.(3)

B. Comparison of the Alloys and the Effects of the Various Environments on the Basis of the Exposure Time Required for Stress-Corrosion Cracking

The alloys are listed left to right in Figure 5 in approximate order of increasing resistance as regards the exposure time required for cracking to occur. In general, failure times were significantly shorter in the high chloride environments (alternate immersion and seacoast atmospheres) than in industrial atmospheres. This effect was very pronounced in the case of alloy 2014-T651. A notable exception to this statement was the case of alloy X7006-T651.

Comparison of the results in the two seacoast atmospheres shows them to be similar but with a slight tendency for Point Judith to be somewhat more severe. This is in spite of the facts that the mean temperature at Point Comfort is about 20°F higher and that the test area there is located closer to the shore line (approximately 110 feet from the water's edge vs 300 feet at Point Judith). The increase severity at Point Judith is believed to principally be the effect of higher wind velocities (frequently of gale force in winter) resulting in greater surf action from the open ocean than in the relatively sheltered Lavaca Bay at Point Comfort.

C. Results in an Experimental Laboratory Environment

For most alloys the results of tests conducted in 3.5% NaCl alternate immersion are quire reliable and the only fault found with the test method is that a more accelerated environment, requiring shorter exposures would be desirable. However, the data obtained in this and other investigations have shown that 3.5% NaCl alternate immersion is not completely conclusive at low stress levels for low copper or copper free Al-Zn-Mg (7000) alloys such as 7079 and X7006 (and 7039, X7002, etc.).

A small investigation was conducted into the ability of a new salt spray test[4] to provide a more satisfactory accelerated environment. The test was conducted in cabinets designed to meet the requirements of the standard ASTM acidified salt spray test (B287-62). The test conditions were as required by ASTM with two exceptions. First, the operating temperature was increased from 95°F to 120°F. Second, instead of a continuous spray, the specimens were intermittently sprayed in six-hour repetitive cycles consisting of 1/2 hour spray, operating per ASTM B287-62, two hours of dry air purge and 3 1/2 hours soak at high relative humidity.

Tests were also conducted in the standard ASTM 5% NaCl continuous spray (ASTM Specification B117-61) since many companies already employ the test for other purposes. Hence, the equipment would be readily available, if it were suited to stress corrosion tests.

The data obtained are given in Table III and compared with the results of other environments in Figure 4. The results showed considerable promise for the acidified intermittent spray, both as regards ability to produce quicker results than alternate immersion and to more closely parallel threshold stresses established in atmospheres. Disadvantages of the test method are:

1. A spray test is not as adaptable to large volume testing as is alternate immersion.

2. Corrosion over the entire surface is not as uniform as in alternate immersion and the position of certain specimens may have to be rotated periodically.

3. The severe localized corrosion that occurred increases the likelihood of a mechanical failure from reduction of cross section areas. Consequently, verification of the nature of failure by microscopic examination is more necessary. In this regard, the per cent loss in tensile strength obtained on unstressed specimens (Table III, Part A), indicates that the alloys evaluated probably should not be exposed more than one week.

The continuous neutral spray showed little merit as a stress corrosion test. The data indicated it would be a less discriminatory environment than alternate immersion and in addition it would also have the disadvantages 1 and 2 listed above for the acidified spray.

CONCLUSIONS:

The following conclusions have been drawn from the results obtained in this investigation employing transverse specimens machined from rolled rod of various high strength aluminum alloys and tempers:

1. Alloy 7075-T7351 and 2219-T87 exhibited the expected high resistance to stress-corrosion cracking in all environments employed, even

with sustained tension stresses in the transverse direction of as high as 75% of their respective transverse yield strengths.

2. A definite susceptibility to stress-corrosion cracking exists for 2014-T651, X7006-T651, 7079-T651 and 7178-T651 when the sustained transverse tensile stress exceeds about 25%Y.S. The probility of failure increases with applied tension stress and approaches 100% at the applied stress of 75%Y.S.

3. In the 3.5% NaCl alternate immersion environment failures generally occur in considerably shorter times than in atmospheric environments. However, the probability of eventual failure in atmospheres is as great or even greater, particularly at lower stress levels. Notable exceptions are the better performance of 2014-T651 alloy and the poor performance of X7006-T651 and 7079-T651 in the inland industrial atmosphere.

4. The acidified, intermittent spray shows promise as an accelerated stress corrosion test. Indications are that it requires shorter exposure periods than the 3.5% NaCl alternate immersion and that it closely parallels threshold values established in atmospheres. The neutral continuous spray is not recommended as a general stress corrosion test method.

STATUS:

The atmospheric tests are tentatively scheduled to be terminated after two years' exposure. Specimens remaining at the completion of the tests will be tensile tested to determine reduction in strength due to corrosion. No new tests are planned for this phase.

Phase II

Evaluation of Surface Treatments and Protective Coatings to Prevent Stress-Corrosion Cracking

OBJECT:

The objective of Phase II was to evaluate the feasibility of preventing stress-corrosion cracking of susceptible alloys by the use of various protective treatments and/or coatings.

MATERIAL:

The material employed was the 2 1/2" diameter rolled rod previously discussed in Phase I (see Table I).

PROCEDURE:

Two types of specimens were used; triplicate 1/2" diameter tensile bars for unstressed specimens and quintuplicate interference fit, ring and plug specimens (Figure 6), for stressed specimens. These specimens were taken from the rod stock in the manner illustrated in Figure 1b and c, respectively.

Thirteen protective systems and two systems of controls were selected for evaluation after a review of the stress corrosion literature [5]. The general types are listed in Table IV and the detailed application procedures are given in Appendix C-1. In the case of stressed specimens, all protective operations were made after the application of stress with the exception of shot peening (ring enlargement during peening necessitated calculation of the required interference after peening).

The fifteen systems evaluated can be categorized as follows:

1. Controls: System 1 - no protection, System 7 - normal minimum protection procedure for aluminum employed by NASA.
2. Surface Working: System 2 (shot peening).
3. Galvanic Coatings: Systems 3, 4 and 13.
4. Organic Paints: Systems 8 through 12.
5. Combinations: Systems 14 and 15, shot peening or metallizing plus organic paint.
6. Anodic Oxide Coatings: Systems 5 and 6.

The specimens were exposed to four environments (3.5% NaCl alternate immersion, New Kensington industrial atmosphere (Figure 2) and Point Judith and Point Comfort seacoast atmospheres) according to the schedule given in Table V. Certain stressed specimens for the New Kensington and Point Comfort atmosphere were exposed with an intentionally damaged coating. The technique employed was a peripheral scribe mark along the center line of the 1/2" width, machined through the coating to a depth of 2 $\pm$ 1 mils into the underlying metal.

EXPERIMENTAL RESULTS:

A. Unstressed 1/2" Tensile Bars

The per cent reduction in mechanical properties resulting from corrosion of the unstressed longitudinal tensile bars exposed to the 3.5% NaCl alternate immersion is summarized in Table VI and the conditions of various systems are illustrated in Figures 7 to 11.

The data obtained did not vary significantly by alloy with the exception that the losses tended to be somewhat higher for alloy 2024-T351. This probably resulted from the alloy's inherent tendency to intergranular attack, whereas, the other alloys incur primarily pitting attack. (Note: Data on the individual alloys were previously reported in the 7th Quarterly Report.) In interpreting the data in Table VI the following points should be kept in mind.

1. Reductions of 2% or less in tensile strength and of 10% or less in elongation are not necessarily significant as original properties can vary by this amount at different locations along the rod.

2. Reduction in elongation is primarily a notch effect, being affected by even superficial corrosion, with appreciable scatter to be expected. These data can be interpreted only qualitatively and are used merely to detect inception of corrosion prior to a significant decrease in tensile strength.

3. The increased reduction in elongation on the peened and metallized specimens (Systems 2, 3, 14 and 15) is not solely a corrosion effect but is due in part to increased roughness and surface hardness caused by peening and by grit blasting prior to metallizing.

These data indicate that:

1. All systems other than 2 and 4 afforded substantial protection against general corrosion as compared with an as-machined surface.

2. The organic paint systems offered the best protection being closely followed by the Alumilite 205 treatment.

3. Shot peening has no appreciable effect, pro or con, on the resistance to general corrosion.

4. Zinc electroplating, at least in these tests, was adverse. This resulted from the tendency for the plating to lift away from the underlying metal to produce a more aggressive local crevice corrosion rather than the desired electrochemical protection.

In view of the low losses in alternate immersion it has been decided to complete at least two years of atmospheric exposure before making any tensile tests.

B. Stressed Rings

The up to date status of the protected stressed specimens is given in Tables VII and VIII. These data are summarized in Table IX and compared graphically in Figures 12 to 14. The two most contrasting environments (alternate immersion and industrial atmosphere) were used for Figures 12 and 13 and the seacoast atmospheric data fall in between these two.

In general, the additional one year of exposure has strengthened the tentative conclusions made in the one year summary report (Reference 2). Also, the data show that Al-Cu alloys, as exemplified by 2014-T651, were benefited more by the protective systems than Al-Zn-Mg-Cu alloys, exemplified by 7079-T651. Alternate immersion has proven to be the most severe environment, closely followed by Point Judith seacoast atmosphere, then by Point Comfort seacoast atmosphere, with New Kensington industrial atmosphere the least severe. Observations made on the protective systems follow.

Controls

System 1

The performance of the as-machined controls was as expected; specimens of the four susceptible alloys all failing relatively rapidly. As shown below, the data on these specimens illustrate the relative severity of the four environments.

Days Required for Failure of All Five As-Machined Control Specimens

Alloy	A.I.	P.J.	P.C.	N.K.
2014-T651	6	14	35	167
7079-T651	17	43	87	76

In contrast, the 2219-T87 and 7075-T7351 specimens dramatically illustrate the advantage of an inherently resistant alloy. The only failures to date have been the 7075-T7351 specimens exposed to alternate immersion and then only after the very prolonged exposure of 446 to 553 days (see Table VII).

The 7075-T7351 failed rings differed from those of the four susceptible alloys. In addition to the main fracture which resulted in eventual failure, the rings contained numerous secondary cracks part way through the specimens (Figure 15). Also, while microscopic examination did reveal intergranular cracking of the type illustrated in Figure 3, it was signficant that cracks always emanated from sites of deep surface attack which would act as stress risers. The fact that the stress riser action of these surface pits was substantial was indicated by the further observation that many of the cracks were either totally or partially transgranular (Figure 16). Hence, failure of these specimens was due in part to mechanical rupture as well as to stress-corrosion cracking.

Some corrosion had occurred on the faying surfaces of the 7075-T7351 rings and plugs, interjecting the possibility of increased applied stress by corrosion product build up on these surfaces. Consequently, two of the 2219-T87 bare specimens were removed from alternate immersion after 565 days and disassembled (see note Table VII). Despite appreciable edge attack, no corrosion had occurred on the faying surfaces. It was concluded, therefore, that the faying surfaces of the 7075-T7351 specimens most likely corroded after cracking had initiated and allowed the solution to enter. Microscopic examination of the two 2219-T87 rings showed them to be free of any incipient cracking.

System 7

Application of a single coat of zinc chromate primer has been able to prevent stress-corrosion cracking only for the 2014-T651 specimens exposed to New Kensington. It did increase specimen life in all cases by at least a factor of 2 and was not sensitive to damage marks, probably because of the inhibitor action of the chromium ion (see

Figures 12 and 13). As such, the system has merit only in preventing general corrosion and in minimizing stress corrosion during short time storage or assembly. Of course, the system was intended merely to establish a minimum baseline.

Surface Working

System 2

Shot peening prevents stress-corrosion cracking by placing the peened surface under residual compression stress thereby eliminating one of the essential requirements of stress-corrosion cracking; namely, sustained tension stress. Consequently, peening is an effective preventative only if: (1) All exposed surfaces originally under tension stress are peened, and (2) the resultant compressive surface layer remains intact so that underlying tensile stresses are not exposed. It is to be expected that the effectiveness of a good peening treatment would vary with both the inherent resistance of the alloy to general surface corrosion and with the severity of the environment. The data obtained shows this to be the case. As illustrated in Figure 14, peening was of little benefit to 2014-T651 in alternate immersion where the alloy incurs severe surface attack but was of appreciable benefit to alloy 7079-T651 though it did not prevent failure. In the less severe seacoast atmosphere (Point Judith) peening did improve the performance of 2014-T6 and prevented failure on 7079-T651, while in the still less severe New Kensington atmosphere both alloys have been completely protected to date. Metallographic examinations of failed specimens have substantiated the above observations. They have shown that the attack in the highly worked surface layer is essentially pitting (Figure 17) but that once this layer is penetrated intergranular attack and subsequent cracking can ensue (Figures 18a and b). Also, they verified the difference in inherent resistance to general attack between alloys that was indicated by visual examination (Figure 7) and by reduction in tensile strength of unprotected 1/8" diameter bars (Table II). This effect of surface stresses has been observed by other investigators who have shown even that surface stresses of opposite sign (compression vs tension) have negligible effect if they act only over a thin layer so as to be readily penetrated by either a mechanical scratch or general corrosion (References 6 and 7).

Galvanic Coatings

System 3

The performance of the metallized (7072 alloy) specimens continues to be good with failure occurring only for 7079 alloy and even here on only 4 out of 30 specimens. Metallized coatings are porous and environmental solutions will permeate them and reach the underlying metal. To be highly effective, therefore, the coating must be sufficiently anodic to provide electrochemical protection. It is significant that failure has been limited to 7079-T651 which has a solution potential close to that of 7072 and can receive only marginal protection. Metallizing with a suitable aluminum alloy, therefore, can be an effective protective method. The only apparent drawback is that the relatively thick coating required to insure good coverage will impart a weight penalty.

System 4

While showing a good performance, the zinc plated specimens have proven to be less resistant than the metallized ones, 16 failures having occurred on 3 of the 4 alloys tested (Note: Again the majority of the failures (10) were for 7079 alloy, the most difficult of the four to protect electrochemically). The lower performance of the zinc electroplate compared with the metallized aluminum is attributed to relatively quick consumption of the zinc, particularly in the alternate immersion environment. The data obtained on the unstressed tensile bars (Table VI) supports this. Another related drawback is that zinc plating would result in even greater weight increase than aluminum metallizing.

System 13

The heavily zinc pigmented paint was an attempt to develop a galvanic coating that could be applied with normal paint procedures but considerable difficulty was encountered in keeping the zinc in suspension during painting. Results showed the coating deteriorated in the severe environments of alternate immersion and Point Judith atmosphere, resulting in loss of adhesion. Also, it was somewhat sensitive to mechanical damage marks in the other two environments. This indicates the protection afforded was not strictly electrochemical but due in part simply to a barrier film.

Because of the difficulty in application and rapid deterioration this coating is not recommended as an effective protective measure.

Organic Paints

Systems 8 to 12

As a whole the epoxy-polyamide and polyurethane coatings, when used with a primer, afforded good protection provided the paint envelope was not damaged. (See Table IX and Figures 12 and 13.) Use of a primer (strontium chromate epoxy primer) was of some benefit for the epoxy-polymide topcoat and mandatory for good adhesion for the polyurethane. The principal disadvantage of these systems is that they provide merely a barrier layer and are ineffective once mechanical damage occurs.

Combinations

Systems 14 and 15

As would be expected, the best protection was afforded by the combination of an organic paint system with surface working (System 14) or with a galvanic coating (System 15). No failure has as yet occurred with System 14 and only three with System 15 (all confined to 7079-T651 alloy which cannot be completely protected by 7072 metallizing). Even for these systems, though, eventual failure with sufficient exposure is to be expected. Hence, protection is in the form of extended life rather than immunity. This extension, though, is considerable, already being over 100 times that of bare 2014-T651 exposed to alternate immersion and over 40 times that of 7079-T651.

Anodic Oxide Coatings

Systems 5 (Alumilite 205) and 6 (Alumilite 226)

While excellent for their designated purpose (prevention of general weathering) neither of the anodized coatings afforded any significant protection against stress-corrosion cracking (Table IX).

A side line investigation on the 7178-T651 rod indicated the effectiveness of the Alumilite 226 process could be improved by a sealing treatment, particularly a dichromate seal. Average time to failure in the 3.5% NaCl alternate immersion for unsealed rings was 6 days as compared with 22 days for a boiling water seal and 315 days for a dichromate seal.

The data in Tables VII and VIII show that the Alumilite 205 treatment caused a slight acceleration in time to failure of 7079-T651 specimens, as compared with an as-machined specimen. Repeat tests, at stress levels of 75, 50 and 25%Y.S., on the 7079-T651 rod in this investigation, plus a second randomly selected rod item, confirmed this effect. However, they showed the effect was only an acceleration of failure time and that the threshold stress below which failure is not expected was unchanged.

Summation

The overall failure data to date are summarized in Table IX.

Group A

Outstanding systems are Group A in Part B; the two combination systems (14 and 15) and metallizing (3). The few failures that occurred for Systems 3 and 15 must be discounted to some extent because they were all 7079-T651 for which 7072 is not an ideal metallizing alloy as regards maximum galvanic protection.

Group B

Zinc electroplate (4) had the next best performance record but was definitely inferior to aluminum metallizing. Therefore, this system appears to be of merit only for cases where galvanic protection is desired but metallizing is not feasible.

Shot peening by itself is effective for alloy environment combinations for which the amount of general surface corrosion will be insignificant or only slight and where only minor mechanical damage (of less depth than the shot-peened surface layer) may occur.

Use of an organic coating, such as the epoxy-polyamide with a primer should be considered for applications where the possibility of mechanical damage is remote.

Group C

The remaining systems are inferior to the preceding ones and hence are not recommended.

CONCLUSIONS:

The following conclusions have been drawn from the results obtained in this investigation employing rolled rod of various high strength aluminum alloys and tempers:

1. The optimum method of preventing stress-corrosion cracking in aluminum alloys, of course, lies in the proper design so as not to introduce high sustained tension stresses in the short transverse or transverse directions.

2. The second best method is the use of an inherently resistant alloy such as 2219-T87 or 7075-T7351.

3. When susceptible alloys must be used, the best protection appears to be the use of a combination of shot peening or metallizing plus a top coat of epoxy-polyamide or equivalent coating.

4. Galvanic coatings of metallized aluminum or zinc electroplate by themselves afford a substantial degree of protection but carry a weight penalty which may be prohibitive in certain cases. Metallized aluminum is the preferred coating of the two.

5. Good protection is also possible from the use of organic coatings such as epoxy-polyamide or polyurethane paint so long as the paint envelope remains intact and is not broken by inadvertent mechanical damage. The epoxy was the better coating

of the two evaluated and the polyurethane should only be used over primed surfaces.

6. Shot peening is capable of providing good protection provided that all the tension surfaces, which are or may be exposed, are adequately peened, and so long as severe surface corrosion is not encountered. If the latter is expected, then additional protection against general corrosion must be provided to prevent rapid penetration of the compressive layer produced by peening. Shot peening is believed to be most effective when performed after the sustained tension stress has been introduced.

7. Anodic films such as Alumilite 205 and 226 are not effective methods of preventing stress-corrosion cracking.

STATUS:

All environments are scheduled to complete at least two and possibly four years of exposure. Upon termination of exposure the unstressed tensile bars will be tested to determine reduction in strength due to corrosion. No new tests are planned for this phase.

Phase III

Development of Rapid Criteria for Stress Corrosion Resistant Tempers of 2219 Alloy Products

INTRODUCTION AND OBJECT:

The development of aluminum alloys and tempers with a high order of resistance to stress-corrosion cracking, such as 2219-T851, and -T87, 7075-T73, etc. has generated a need for rapid tests that can be used to demonstrate the capability of these materials. Present specifications for these materials require a 30-day stress corrosion test by alternate immersion in 3.5% NaCl solution. Faster criteria are desirable, and successful methods have been found for 7075-T73 (8) (9). The conductivity measurements and potential measurement techniques used for 7075-T73, however, are not adequate for 2219 alloy. On the basis of a review of published literature and of unpublished data available at the Alcoa Research Laboratories the work in this program was directed along lines to accomplish the following objectives for 2219 alloy:

1. Develop a more highly accelerated stress-corrosion cracking test.
2. Develop a potential measurement technique that may be correlated with the resistance to stress-corrosion cracking.

A. Accelerated Stress Corrosion Test

Prior studies by Alcoa Research Laboratories (1) showed that an electrolyte containing 3 g/l NaCl + 36 g/l CrO_3 + 30 g/l $K_2Cr_2O_7$ was an aggressive cracking medium for a variety of aluminum alloys. In this solution, however, stress corrosion resistant tempers failed almost as quickly as susceptible materials. The failures were associated with severe pitting and intergranular corrosion, and it was difficult to determine whether the failures resulted from stress-corrosion cracking or simply from excessive localized corrosion. On the other hand, other experience with an electrolyte containing 53 g/l NaCl + 50 g/l Na_2CrO_4 showed that this relatively non-corrosive solution was not aggressive enough, and stress corrosion test results were too erratic. Studies in this contract program were aimed at finding an electrolyte between the two extremes that would provide a practical accelerated test.

Electrolyte Screening Tests Using 2219-T37 Sheet

Solutions representing ten combinations of NaCl, CrO_3 and $K_2Cr_2O_7$ were made up with distilled water, and a pilot stress corrosion test was conducted in each, using highly stressed "preformed" specimens of 2219-T37 sheet. The tests were conducted using the usual alternate immersion cycle (10 minutes immersion followed by 50 minutes drying in air). A description of the test solutions and the times to fail of the stressed specimens are given in Table X. On the basis of a microscopic examination of specimens that failed in each electrolyte, solutions F and G were chosen for further study in comparison with solution H and the standard 3.5% NaCl solution.

Stressed "preformed" specimens of 2219-T37 and the stress corrosion resistant -T87 temper gave the following results in these electrolytes:

	Days to Failure	
Electrolyte	-T37	-T87
3.5% NaCl	3/3 (5, 5, 5)	0/3 (OK 30)
F	2/2 (0.5 - 1)	0/2 (OK 30)
G	2/2 (0.5 - 1)	0/2 (OK 30)
H	2/2 (0.2, 0.2)	2/2 (10, 11)

Under more frequent inspections than made previously, it was observed that the susceptible -T37 temper specimens were cracked much more quickly in F and G electrolytes than in the 3.5% NaCl solution. It seemed especially significant that the F and G electrolytes, like the 3.5% NaCl, did not crack the -T87 temper specimens, whereas, the more corrosive H electrolyte did.

Evaluation of Selected Electrolytes

Further stress corrosion tests were conducted with these four electrolytes using transverse 0.125" diameter tensile bars machined transversely (Figure 1a) from pieces of 2219-T37 rod that had been given various periods of aging at 325°F. The purpose of the various agings was to develop different degrees of resistance to stress-corrosion cracking including items of borderline susceptibility. Duplicate specimens were stressed to 75% of their respective yield strengths and exposed along with duplicate unstressed specimens of each item. Whenever a stressed specimen failed, a corresponding unstressed specimen was removed from the test solution, cleaned in concentrated nitric acid and tensile tested. All stressed specimens that survived 30 days' exposure in F, G and H electrolytes, and the corresponding unstressed specimens were tensile tested. The more resistant items were allowed to run out to 84 days before the test was concluded in the 3.5% NaCl solution.

An attempt was made to analyze the stress corrosion test data using the Jones method (11). With this method a percentage stress corrosion susceptibility is calculated to represent the percentage of the loss in strength of a stressed specimen that is caused by stress corrosion, either by actual failure of the specimen or by acceleration of attack.

$$\% \text{ Stress Corrosion} = \frac{S_s - S_u}{S_s} \times 100, \text{ where}$$

When stressed specimen does not fail,

S_s = % loss in tensile strength of stressed specimen.

S_u = % loss in tensile strength of unstressed specimen exposed for same period as the stressed specimen.

When stressed specimen fails, S_s is determined as follows:

$$S_s = \frac{TS - P}{TS} \times 100, \text{ where}$$

TS = Tensile strength of the material.

P = Stress applied to specimen.

The test data are summarized in Table XI.

The Percentage Stress Corrosion Factors computed for the 3.5% NaCl test showed some scatter, but tended to decrease as the aging time was increased. On the basis that a 30-day test is adequate for this alloy and size of test specimen, then a factor of something less than 40% should be required to assure a high resistance to stress-corrosion cracking. With the other electrolytes, Factors below about 50% were not obtained even for the fully aged -T87 temper material which had an average factor of 8% in the 3.5% NaCl solution. This type of analysis indicates that electrolytes F, G and especially H may be too aggressive for a practical stress corrosion test.

On the other hand, when the average specimen life was plotted against the metal aging period (Figure 19) the performance of electrolytes F and G appeared similar to that of 3.5% NaCl, whereas, that of electrolyte H was quite different. It appears that about a 7-14 day test in electrolyte F or G would be just as effective as a 30-day test in 3.5% NaCl. The photograph in Figure 20 shows another possible advantage of the G electrolyte in that it is less corrosive than 3.5% NaCl.

CONCLUSIONS AND STATUS:

Electrolytes F and G appear sufficiently promising to justify further investigation. A repeat test with greater replication of test specimens will be made using an "average" F-G electrolyte containing 3.5% NaCl, 0.5% CrO_3 and 1.0% $K_2Cr_2O_7$.

B. Potential Measurements

The work in this part of the contract was directed toward the development of solution potential measurements to evaluate the stress corrosion performance of 2219 alloy products. The use of solution potentials to evaluate the corrosion performance of aluminum alloys is not new. As long ago as 1945, Mears, Brown and Dix (12) demonstrated a relationship between the solution potential of 2024 alloy products in NaCl-H_2O_2

solution and the period of artificial aging. More recently, in 1959, Dix, Anderson and Shumaker (13) demonstrated that the stress corrosion performance of Al-Mg alloy products can be evaluated by solution potential measurements in NaCl- H_2O_2 solution provided that special techniques are used. Still more recently, Ketcha and Hanie (14) used solution potential measurements in sodium chloride solution to evaluate aspects of metallurgical structure related to the stress corrosion performance of 2024 alloy. And, in 1963, King, Lifka and Willey (8) of the Alcoa Research Laboratories developed solution potential measurements in acidified sodium chloride solutions for evaluating the stress corrosion performance of 7075-T73 alloy products. Unpublished work at the Alcoa Research Laboratories has also shown that the solution potential of 2219 alloy products varies with the resistance to stress corrosion.

The difficulty with these measurements is that the differences between susceptible and non-susceptible products can be very small, amounting in some instances to only a few millivolts. As a result, they can be used only when the strictest attention to experimental technique is exercised; and even under these conditions, they do not provide complete reliability. They are not suitable for quality control testing in a plant.

In the work carried out under the contract, practically all the effort was directed toward the development of measurements in an organic electrolyte consisting of a mixture of methyl alcohol and carbon tetrachloride. The use of an organic electrolyte for solution potential measurements is new. The fact that aluminum alloys react with a mixture of methyl alcohol-carbon tetrachloride has been known by the Alcoa Research Laboratories for some time (although insofar as is known, the information has not been published). Fortuitously, it turned out that the reaction of this electrolyte with 7075 alloy was investigated at the Alcoa Research Laboratories a year or so before the contract was awarded. In this work, a large change in the solution potential of 7075 alloy was found associated with a small, gradual change in metallurgical structure; and following this lead further, it was demonstrated that solution potential measurements in the electrolyte could be used to establish the stress corrosion performance of 7075 alloy products.

PROCEDURE:

Except for the difference in electrolyte itself, the procedure used for measurements in methyl alcohol-carbon tetrachloride is practically the same as that used for conventional measurements in NaCl-H_2O_2 solution. As discussed later, the composition of the solution depends upon the product to be evaluated. A liter of solution is prepared at one time. This solution is then conditioned by the addition of a piece of 0.064" x 1" x 1" 2219 alloy sheet. About 30 minutes is required for the piece of sheet to react completely with the solution. The resulting solution, which is pale yellow, is ready for use when it cools to room temperature. Without preconditioning, longer periods are required to obtain steady solution potentials.

No special preparation of a specimen is required other than degreasing. A surface area of approximately 0.5 sq. in. has been used, but this area does not have to be controlled. The specimen naturally should be taken from the location where stress corrosion performance is of the greatest concern; in general, this is from the mid-way plane of the product.

Care must be exercised to guard against volatilization of the solution sufficient to change its composition significantly. For the measurements made so far, at least 500 milliliters of solution have been used. Up to 10 specimens have been measured at the same time in this volume of solution. Fresh solutions have been used for each group of measurements, but it is quite likely that a solution can be used longer (*).

The data in Figure 21 illustrate the experimental variations that can be expected in duplicate measurements as well as the magnitude of the difference between as-quenched and artificially aged tempers. The solution potential after 20 minutes is taken as the equilibrium value. Longer periods result in a change of only a few millivolts before a specimen is dissolved completely.

(*) Attention should be called to the fact that both methyl alcohol and carbon tetrachloride are toxic. Proper precautions must be taken to avoid inhalation of their vapors.

EXPERIMENTAL RESULTS:

1. Effect of Aging

-T37 to -T87 Series of Tempers

For developing the procedure for solution potential measurements in methyl alcohol-carbon tetrachloride, a series of samples representing the -T37 and -T87 tempers and intermediate stages in aging between them was selected. These samples were prepared from plant fabricated 2 1/2" diameter 2219-T37 rod. Sections of this rod were artificially aged at the Alcoa Research Laboratories for 3, 6, 8, 10, 12, 14 and 20 hours at 325°F to cover a range of susceptibility to stress corrosion. The tensile properties of the samples and the results of stress corrosion tests upon them in 3 1/2% NaCl solution by alternate immersion are summarized in Table XI. As is obvious from this table, samples aged up to 8 hours were susceptible to stress-corrosion cracking, samples aged 10 to 12 hours were partially susceptible, that is borderline, and samples aged 14 hours or more were free of stress corrosion susceptibility.

Measurements upon this series of samples are presented in Figure 22. The large variation in solution potential with each period of artificial aging at 325°F that can be achieved with methyl alcohol and carbon tetrachloride is quite evident. For any condition of aging, it is clear that a solution can be selected to provide a difference in potential that is several times greater than that obtained in conventional NaCl-H_2O_2 solution.

The selection of criteria for stress corrosion performance obviously depends upon the level of performance desired. For separating susceptible from non-susceptible material, but not for eliminating borderline material, a solution consisting of 60% methyl alcohol and 40% carbon tetrachloride probably would be selected. On the other hand, a 50-50 solution probably would be selected if the criterion is selected for a complete separation of susceptible and non-susceptible materials; that is, a criterion that would not allow any susceptible materials to be accepted. This solution provides the greatest change in slope of the solution potential-aging curve at the line of demarcation between borderline susceptibility and non-susceptibility; the overall change from this line to the line representing the -T87 temper is also greater than that of any other solution. It must be emphasized, of course, that these criteria are based upon limited data and that more extensive testing may very well change them somewhat.

Work to establish criteria more exactly is in progress. The solution potentials (in the 50-50 solution) of 15 forgings of 2219-T87 alloy produced in the plant varied from -906 to 1060 millivolts; none of these forgings was susceptible to stress corrosion as evaluated in actual exposure to 3 1/2% NaCl solution by alternate immersion.

-T351 to -T851 and -T4 to -T6 Series of Tempers

Results for these two series of tempers are presented in Figures 23 and 24. The samples used for the potential measurements were prepared by artificially aging sections from a 2219-T4 die forged elbow fitting 2 1/2" diameter and 4" thick 2219-T351 alloy plate.

Unfortunately, time did not permit as thorough an evaluation of these products as would have been desired. A comparison of Figures 22, 23 and 24 shows a pronounced effect of cold work upon the variation in solution potential with artificial aging, or alternatively, with stress corrosion performance. As can be seen, the maximum change in solution potential decreased markedly as the amount of cold work decreased. This effect of cold work was investigated in work described in the next section, but unfortunately the work did not include a further investigation of the effect of the composition of the electrolyte. A comparison of Figures 22, 23 and 24 suggests that the change in solution potential in alloys without cold work may have been increased by increasing the percentage of methyl alcohol in the electrolyte. This point is illustrated by the fact that, for alloys containing the most cold work (Figure 22), a 50-50 mixture provides the greatest change in the critical region whereas for alloys containing an intermediate amount of cold work (Figure 23), a 70-30 mixture provides the best results.

Tests are in progress to establish the stress corrosion performance of the alloys in Figures 23 and 24. Until these tests are completed, criteria cannot be established. However, because the curve in Figure 23 for the 70-30 mixture is approximately a straight line of considerable slope, it is clear that suitable criteria can be established for the -T351 to -T851 series of tempers.

2. Effect of Cold Work

The results of tests showing the effect of cold work in greater detail are summarized in Figures 25, 26 and 27. These tests were made when it became evident from the results in the preceding section that the solution potential was influenced to a high degree by the presence of cold work. For the tests, samples of 1/4" thick 2219-T31 alloy plate were re-solution heat-treated, quenched in cold water, cold-rolled 0, 3, 6 and 9%, and finally artificially aged for various periods at 325°F, 350°F and 375°F. It is to be emphasized, of course, that the samples do not duplicate plant production because of the way in which cold work was introduced into them.

In a general sense, the data in Figures 25, 26 and 27 illustrate the effect of the severity of aging rather than the effect of cold work alone. As is obvious, the maximum change in solution potential increased with the severity of aging regardless of how it was produced, whether by cold work, by temperature, or by time. These considerations raise the question that the resistance to stress corrosion of unworked tempers may not be quite equal to that of worked tempers even though the resistance is adequate in all cases.

3. Mechanism of the Reaction of Aluminum with Carbon Tetra-Chloride and Methyl Alcohol

That gradual changes in metallurgical structure should be reflected in such large changes in solution potentials in methyl alcohol-carbon tetrachloride is surprising. The evidence leaves little question that the large difference in potential is related to the deposition and retention of copper on some specimens but not on others. As a result, some specimens act very much like a copper electrode while the other specimens act very much like an aluminum electrode. For example, as shown in Figure 22, a -T37 specimen has a solution potential of about 400 millivolts and a -T87 specimen has a solution potential of about 1000 millivolts; the corresponding values for copper and pure aluminum are 300 and 1100 millivolts, respectively. The presence of copper on a -T37 specimen could be seen visually. On the other hand, none could be seen on a -T87 specimen. These observations are supported by chemical analysis of nitric acid leaches of specimens used for solution potential measurements. A specimen of 2219-T37 with an area of 0.5 square inches retained 35 milligrams of copper while a specimen of 2219-T87 of the same area retained only 1 milligram.

4. Alternate Methods of Measurement (Turbidity)

By implication, at least, the impression may have been given that a solution potential is the only measurement possible in methyl alcohol-carbon tetrachloride for the evaluation of stress corrosion performance. It is important, therefore, to point out that, in the broad sense, the reaction of 2219 with the electrolyte is the basic process for the evaluation of this performance, that solution potential is only a measurement of the process and that other measurements are possible.

Measurement of solution turbidity offers another possibility for following the reaction. From the beginning of the work with methyl alcohol-carbon tetrachloride, it had been observed that the solution, after measurements of potential, varied from practically clear for susceptible specimens to extremely turbid for non-susceptible specimens provided that the variation in susceptibility was reflected in solution potential. X-ray analysis of the residue responsible for the turbidity showed that it consisted primarily of copper. The use of turbidity to evaluate stress corrosion performance is illustrated by the data in Figure 28. The rather striking change in turbidity is evident from the photograph of the solutions themselves, and as can be seen, the actual measurement of light transmission duplicates the course of the potential measurements. Measurement of turbidity is mentioned because it has the obvious advantage that it requires little equipment or skill.

CONCLUSIONS AND STATUS:

In brief, solution potential measurements in a mixture of methyl alcohol and carbon tetrachloride offer a means for evaluating the stress corrosion performance of 2219 alloy products that have been cold worked between quenching and artificial aging. For example, the difference in solution potential of 2219-T87 alloy rod aged to reflect borderline and non-susceptibility to stress-corrosion cracking was roughly 200 millivolts; in conventional NaCl-H_2O_2 electrolyte, the difference was hardly more than 10 millivolts. Further work is required to adapt the method for products that do not contain cold work. This work should include additional compositions of solutions of carbon tetrachloride and methyl alcohol as well as compounds related to them.

Phase IV

Stress Corrosion Tests of Weldments of Al-Zn-Mg Alloys

OBJECT:

1. Determine the stress corrosion susceptibility of welded joints of the relatively new high strength weldable aluminum alloys, X7002, X7106, 7039 and X7139.

2. Investigate various test procedures to determine the specimen loading method that yields the most practical interpretation of the test results.

MATERIAL:

The following alloys and tempers were evaluated:

1/8" Thick Sheet	3/8" Thick Plate	1" Thick Plate	12" Thick Hand Forging
X7002-T6	X7002-T651	X7106-T6351	X7106-T6352
X7106-T7	X7106-T6351		
7039-T6	7039-T651		
X7139-T6	X7139-T6351		

All items were mill fabricated under metallurgical supervision. The chemical compositions and tensile properties were representative of these alloys (Table XI).

PROCEDURE:

A. Welding

Sheet and plate thicknesses of 1/8" and 3/8" were chosen for study as they are representative of the gauges likely to be used commercially. These gauges, especially the 3/8", reflect maximum heat effects from welding in addition to being convenient sizes for testing. The 1" thick plate was chosen for limited testing to demonstrate effects of multi-pass welding. The majority of the welds were made by the (Direct Current Straight Polarity) Tungsten-Inert-Gas process which is most applicable commercially while the (Direct Current Reverse Polarity) Metal-Inert-Gas process was used for limited comparisons. Except for alloy 7039, which was welded with the Al-Mg filler, 5183, the alloys were welded with the Al-Mg-Zn filler, X5180.

Two 12" x 24" plates were butt-welded to form 24" square panels by the Alcoa Process Development Laboratories. Weld procedures were recorded and are given in Appendix C-2. All panels were radiographed, and the specimens selected from the panels on the basis of weld soundness. The 1/8" thick sheet of all alloys presented some difficulty in obtaining sound welds and had to be re-welded. No difficulty was encountered with the 3/8" thick plate or the 1" thick X7106-T6351.

Tensile properties were determined by means of standard full section specimens and representative values were obtained for these alloys (Table XI).

B. Types of Stress Corrosion Specimens

Beam Specimen

The most commonly used specimen for stress corrosion testing weldments of aluminum alloys has been the beam type specimen stressed in bending (Figures 29 thru 32). The specimen has been used extensively at the Alcoa Research Laboratories and by others (15). Stress corrosion tests are generally made at a stress level within the elastic range (75% of the yield strength) wherein the stresses are proportioned to the beam deflection. Although a uniform cross section is assumed, it is realized that when the weld beads are left intact, an unknown concentration of stress will occur at the weld bead fillets. The deflection necessary to stress a pair of specimens is determined by the following formula:

$$d = \frac{2\ fa}{3\ Et}\ (3\ L - 4a)$$

d = total deflection of two beams on section through bolts relative to center supports, in.
f = extreme fiber stress in center span, psi.
a = distance between center of support and bolt, in.
L = distance between center of bolts, in.
t = thickness, in.
E = modulus of elasticity, psi.

The procedure for stressing is to tighten the bolts uniformly until the desired beam deflection at the centerline of the bolts is obtained which corresponds to the desired extreme fiber stress in the center span.

The extent to which stresses in welded beam specimens agree with calculated values was determined from tests on specimens of MIG welded (X5180 filler) 1" thick X7106-T6351 plate. Stresses were calculated from strains measured in the parent material, outside the heat affected zone, about 0.24" from the edge of the weld bead (location of fracture in mechanical property specimen) as shown in Figure 32. Strains were measured using type C12-121 foil electrical resistance strain gauges.

The test procedure was as follows: The specimens were loaded in tension in a testing machine in order to determine the relationship between stress and strain at the gauge locations. Specimens were loaded in increments until the maximum stress (gauge no. 3 in the parent material) reached about 75% of the yield strength (Figure 33). Next, the specimens were placed in the bending fixture and loaded in increments until the gauges in the heat affected zone (gauges 1 and 2) showed the same strain as that recorded in the tension test when the gauge in the parent material (gauge no. 3) was stressed to 75%Y.S. (Figure 34). From the test results, it may be concluded that:

1. For tension loading, the average measured strain in the parent material was in close agreement with the strain corresponding to the applied load. The stresses adjacent to the weld ranged from 1.16 to 1.21 times the stress in the parent material.

2. Because of warpage due to welding, the specimens underwent considerable bending during tension loading. It might be noted, however, that in the case of thinner specimens (as for example the 1/8" specimens) the bending stresses produced when a warped specimen is straightened in the fixture are small and may be ignored.

3. In the bend test, the stress in the parent material was about 1.05 times the calculated stress corresponding to the measured deflection; while the stress adjacent to the weld bead ranged from 1.09 to 1.25 times the calculated value.

The above results show that the standard beam formula for calculating stresses in weld specimens may underestimate the stresses adjacent to the weld by about 20 per cent. Moreover, in the notch (fillet) at the edge of the weld bead, the stress concentration will cause the maximum stresses to be appreciably higher than the values measured in these tests.

Tension Specimen

Recent weld tests at the Alcoa Research Laboratories and the Rocketdyne Division of North American Aviation, Inc. have indicated that stress corrosion test results obtained with butt-welded specimens axially stressed in tension (Figure 35) can be different than when stressed in bending (Figure 31). Both methods of stressing operate on the constant deformation principle, in that the deflection required to initially load the specimen is maintained essentially constant during the test. In loading the tension specimen in the constant deformation fixture (Figure 36), the sides were squeezed toward the specimen employing several nearly equal increments by turning the specimen over 180° each time until the desired strain reading was obtained. The strain which is equivalent to the desired stress was measured on both sides of the specimen by means of an electrical extensometer placed just outside the heat affected zone. Strains were read to within $\pm$ 1 micro-inch over a half-inch gauge length. The above constant deformation fixture was designed after that used by the Rocketdyne Division.

Other investigators (17, 18) have used direct tension loading methods employing dead load, which would be expected to give an even more severe test. While the latter method has a possible advantage of producing a more rapid detection of stress corrosion susceptible materials, it could have the disadvantage of causing failures of resistant materials as a result of the mechanical overload after corrosion has occurred. The fixture designed by Alcoa for employing constant load is shown in Figure 37. This fixture is loaded by simply tightening the nut until the desired strain reading is obtained as illustrated in Figure 38. Care must be exercised in loading both the constant deformation and constant load fixtures so that a uniform load is obtained on each side of the specimen.

H-Plate (Residual Tension)

The H-plate specimen was designed for testing thick plate in direct tension by taking advantage of the residual stresses developed when welded under restraint so that excessively large and expensive loading devides would not be required. A specimen used by the Engineering Design Division of the Alcoa Research Laboratories for the determination of welding residual stresses in plate was modified for this purpose. A typical H-plate stress corrosion specimen is shown in Figure 39. Tensile stresses are developed across the weld as a result of the thermal mismatch and plastic deformation accompanying welding of the center strut. In general, the stress magnitude will depend on the length of the center strut, the relative cross sectional areas of the center and side struts, the welding technique and the extent to which mismatch is introduced into the specimen just prior to welding, either by heating the center strut or chilling the side struts. Welding of a representative H-plate is shown in Figure 40.

The H-plate specimens are 18" x 18" pieces of sheet or plate with two slots forming the leg of the H (1" wide x 5" long slot centered 6" from each side) and the restraint weld being the center of the H. The weld in this center strut is originally 4" in length but reduced to 2" before testing. The plates were positioned so that the prinicpal welding stress would be transverse to the rolling direction of the plate. Stiffener plates 1/4" x 4" were fastened to the 1/8" and 3/8" specimens to act as heat sinks. In the case of the 1/8" specimens it was necessary to keep the stiffeners attached during exposure to prevent buckling. In order to prevent galvanic corrosion, the entire 1/8" thick specimen was painted except for the 2" wide center strut.

The welding details of the H-plate specimens are covered in Appendix C-2. However, the following is a typical procedure employed in the preparation and welding of H-plates (for 3/8"):

TIG welded specimens required no weld preparation while the MIG specimens had a 60° V groove with a 1/16" land and no gap. Specimens were then pre-chilled overnight in dry ice. Just prior to welding, the specimens were removed from the cold chest and the center strut preheated with a torch to 200°F as measured by electrical pyrometer. The specimens were welded, such that the elapsed time between removal of the specimen from the cold chest and completion of the weld was kept to a minimum. Welding tabs and stiffeners were then removed and the center strut machined to 2" in length for testing. Stresses due to welding and to reducing the width of the center strut were determined from Berry strain gauge readings obtained on 2" gauge lengths in the parent material, as shown in Figure 39.

Stress Levels

The specimens loaded in bending and in tension were stressed to either 75% of the as-welded yield strength or

75% of the post-weld yield strength as determined by standard full section specimens with the weld bead intact. Yield strength was measured at 0.2 per cent off-set in a 10" gauge length for the 3/8" and 1" specimens and a 2" gauge length for the 1/8" specimens. The weld bead was left intact on all stress corrosion test specimens since this represents the manner in which welds remain in the majority of the commercial applications. However, limited tests have been planned to evaluate welded specimens with the beads machined off as it is recognized that this procedure is also employed, for instance in tankage.

C. Test Environments

All materials were exposed to the ARL 3.5% NaCl alternate immersion test at room temperature. This test was described in detail under Phase I. A photograph of the several types of specimens in the alternate immersion tanks is shown in Figure 41. In addition, all materials were exposed to an inland industrial atmosphere at New Kensington, Pennsylvania, and to a seacoast atmosphere at Point Judith, Rhode Island. A portion of the New Kensington atmospheric facilities is shown in Figure 2.

D. Evaluation

Periodic (daily for alternate immersion and weekly for atmospheric tests) visual inspections for evidence of cracking were performed on the stressed specimens, and failures recorded. As failures occurred, the specimens were cleaned in concentrated nitric acid and representative specimens submitted for microscopic examination to determine nature of failure. At the completion of the test period (6 months for alternate immersion and minimum 1 year for the atmosphere), the stressed specimens which have not failed, and the unstressed specimens removed at periodic intervals, are to be tested to determine the reduction in tensile properties caused by corrosion.

Various characteristics of the weldments were determined by metallographic examination and by hardness and solution potential measurements.

EXPERIMENTAL RESULTS:

Tests have been in progress from 2 to 5 1/2 months. The stress corrosion data are summarized in Tables XII through XVI. Analysis of these data is not complete and any conclusions reached must be considered tentative at this time.

A. Comparison of Alloys

As-Welded

The resistance to stress corrosion of all four alloys, X7002, X7106, 7039 and X7139, in the as-welded condition has been very good in all thicknesses. Several failures have been observed with the 1/8" thick sheet (Table XII) after approximately 4 months' exposure to the 3.5% NaCl alternate immersion. These were associated with severe localized corrosion in the heat affected zone. However, the failure observed under constant load for X7106-T6 was established metallographically as a mechanical failure resulting from the severe localized corrosion of the heat affected zone. The others are in the process of being examined metallographically.

Obviously, there is a disadvantage in having to examine every failure metallographically but appears necessary for specimens tested under constant deformation as well as constant load when the extent of corrosion becomes severe. For this reason, it is planned to terminate the alternate immersion tests at 6 months' exposure. This period actually is too long for this environment.

1. Corrosion of Unstressed Specimens

The as-welded specimens suffered considerable attack in the heat affected zone in the unstressed condition after 3 months' exposure in the 3.5% NaCl alternate immersion test as shown in Figure 42. The losses in strength were about the same for all of the alloys, ranging from 15 to 19%. Also, observe that in the case of the parent metal only X7002-T6 showed any appreciable loss in strength as a result of corrosion. This is related to its higher copper content as compared to the other Al-Zn-Mg alloys.

Work is in progress to determine the type and depth of attack of the various regions of the welded specimen.

Visual examination indicated that the post-weld aged specimens did not exhibit selective attack at the heat affected zone.

Effect of Post-Weld Aging

As indicated in Table I post-weld aging offers a substantial improvement in weld strength for all alloys and from this standpoint is highly desirable. However, as indicated in Tables XII, XIII, XIV and XV, the post-weld aging treatment employed generally lowered the resistance to stress corrosion as shown by all methods of loading.

1. Face Versus Root in Tension

In the case of the 1/8" thick sheet it was significant whether the face or root was stressed in tension by bending; there being no failure in beam assemblies with the root stressed in tension failed. It has also been observed with the direct tension specimens that failure tended to initiate at the face of the weld (Figure 43).

2. Level of Stress

Because of the rapid failure of the post-weld aged items, tests at lower levels of stress to determine the level at which stress-corrosion cracking is eliminated were planned in the continuation of the work in Phase IV. Preliminary indications are that lowering the level of stress upon post-weld aged yield strength to 28 ksi (75% of the as-welded yield strength) did not improve the resistance to stress corrosion, as early failures, 3 to 6 days, were observed when stressed by constant load and exposed to the 3.5% NaCl alternate immersion test. After nearly 90 days' exposure

(Table XVI), the H-plate specimens with average stresses ranging from 9.1 to 17.2 ksi have shown no evidence of cracking of X7106-T6. But a failure has been observed with X7139-T6 after 88 days in the New Kensington atmosphere. This specimen had an average stress of 16.8 ksi.

In a previous contract (15) no susceptibility to stress-corrosion cracking was observed at a stress level of 25 ksi (50%T.S.) for 7039-T6 and X7038-T6 alloys in the as-welded and post-weld stress relieved (12 hours 350°F) conditions. The majority of work in the present contract is considerably above 25 ksi and, therefore, cannot be compared. Several other factors also prevent a direct comparison of data. Some of these are differences in test environments - 6% NaCl solution by total immersion vs 3.5% NaCl solution by alternate immersion, thickness of material, filler (D1495, X5039 vs X5180) and post weld thermal treatments (12 hours 350°F vs 8 hours 225°F + 16 hours 300°F).

3. Filler Alloys

The results given in Tables XIII and XIV indicate that 7039-T6 welded with the Al-Mg filler, 5183, was more resistant than either X7106-T6 or X7139-T6 welded with Al-Mg-Zn filler, X5180. While it would appear that an Al-Mg filler alloy such as 5183 or 5356 might be advantageous especially from a resistance to stress-corrosion cracking viewpoint, weld strengths considerably lower than those obtained with X5180 can be expected with heavy sections as also verified in other contract work on those alloys (15).

The results at the present time indicate that X7002-T6 welded with X5180 has better resistance to stress corrosion than the X7106 and X7139 alloys. Other tests (not under this contract) conducted by the Alcoa Research Laboratories have indicated longer times to failure for this alloy in the New Kensington atmosphere; thus it is expected with longer exposures that the susceptibility of X7002-T6 will not be greatly different from the others. Alloy X7002-T6 has the disadvantage of being increasingly difficult to weld in heavier sections; this is related to its copper content.

4. Metallographic Examination of Failures

Failures from all three methods of loading were examined metallographically to verify the cause of failure. All of the post-weld aged specimens failed by intergranular stress-corrosion cracking in the fusion zone. Microstructures representative of the failures are presented in Figure 43. Included for comparison is a fractured tensile test specimen to show the distinction from a tensile failure. Note the smoothness of the tensile test fracture while the stress corrosion failure has small intergranular cracks projecting into the base sheet. Also, observe the beginning of a stress corrosion crack at the toe of the weld bead opposite to the one that fractured.

Effect of Grain Orientation

Slices (3/8" thick) from a X7106-T6352 forging (12" x 24" x 24") were welded in combination with X7106-T6351 plate to simulate applications where the forging welded to the plate material may be stressed in either the long transverse direction or the short transverse direction in relation to its grain orientation. Photographs of macro-etched samples of the forging to plate combinations are presented in Figure 44a and b. These combinations were stressed as beam assemblies (Table XV) and H-plate specimens (Table XVI).

As in the case of the plate, failures occurred with the post-weld aged items only. The fractures consistently occurred in the fusion zone on the forging side with both grain orientations. Figure 45a is representative of a failure in the 3/8" thick material (plate or forging).

1. Paint Protection

It is desirable to know whether painting offers additional stress corrosion protection in service. The paint system used was chosen on the basis of its good performance in Phase II and consisted of Alodine 1200 plus strontium chloride epoxy primer (1 mil) plus epoxy polyamide (2 mils).

As the stress corrosion results in Table XV indicate, painting did not prevent stress-corrosion cracking from occurring, but did delay the time to failure from an average of 22 days to about 73 days in the 3.5% NaCl alternate immersion test.

Effect of Welding Method (TIG vs MIG)

A comparison of the two welding methods, TIG and MIG, was made on 3/8" thick X7106-T6351 plate welded with X5180 alloy filler. The results of the alternate immersion test (Table XIV) show failure for both methods in the post-weld aged condition with about the same specimen life. However, in the New Kensington atmosphere only the TIG welds have failed to date. Thus, the resistance to stress corrosion appears similar for the two methods.

Effect of Corrosive Environment

The 3.5% NaCl alternate immersion and the New Kensington atmosphere thus far seem to be equally potent in producing stress-corrosion cracking of the Al-Zn-Mg alloys; in fact, there is a slight trend that the alternate immersion is the more severe. This is the reverse of corrosion experience with these alloys in other tests at ARL. (Note also the performance of X7006-T651 alloy in Phase I (Table II).) In general, we have found that the New Kensington atmosphere has produced more failures at lower levels of stress than the alternate immersion test. The Point Judith atmosphere produces results which are generally similar to the alternate immersion as to failure but with longer specimen life.

B. Mechanism of Stress Corrosion Failures

While the results for all alloys and thicknesses showed materials in the as-welded condition to be more resistant to stress-corrosion cracking than when post-weld aged, the latter has the distinct advantage of higher strength and less general corrosion of the heat affected zone. It is, therefore, desirable to know more about some of the characteristics such as structure, hardness and solution potential relationships in trying to determine the cause for failure.

Structure

In studying structural differences relating to the stress corrosion susceptibility of post-weld aged material, both light and electron microscopic examinations were made.

Representative microstructures at 500X of various regions across a TIG welded X7106-T6351 plate (3/8" thick) in both the as-welded and post-weld aged conditions are illustrated in Figures 46 and 47, respectively. While evidence of additional precipitation as a result of post-weld aging can be observed in all four regions when Figure 47 is compared with Figure 46, the fusion zone (second from left), which is generally the region of failure, especially showed increased outlining of boundaries with precipitate.

A more intensive study was therefore made of the fusion zone with the electron microscope. Examinations were made of thin foil sections by electron transmission. The thin foil samples were prepared by alternately milling chemically in 40% HCl and warm 20% NaOH solutions. Final uniform thinning was accomplished by electrolytic etching in Lenoir's solution.

An unusually high dislocation density was observed in the fusion zone of the as-welded sample. Also, polygons formed during the very rapid solidification of the weld bead were much smaller along the fusion zone, indicating that a high stress existed in this region. Numerous large precipitates were observed especially in the grain boundaries. These precipitates were identified as M-phase (Zn-Mg) by selected area electron diffraction.

In contrast to the as-welded section, the post-weld aged section was found to exhibit a very low dislocation density and, as expected, zone growth and grain boundary precipitation as shown by Figure 48.

Hardness and Solution Potential Relationships

A comparison of hardness, which reflects strength, and solution potentials, which reflect both corrosion and stress corrosion performance, was made for as-welded and post-weld aged X7106-T6351 plate (3/8") welded with X5180 as shown in Figure 49.

The hardness curves show that the fusion zone is the lowest strength region in the welded joint and is not changed by post-weld aging. The weld itself is strengthened by post-weld aging; however, the strength of the plate is lowered slightly by this second aging treatment. These data support the observation that the mechanical property test specimens generally fractured in the fusion zone.

The solution potential curves indicate that the fusion zone is also the most anodic region. For the post-weld aged material the anodic region is confined to an extremely narrow band; whereas, in the as-welded material this region is significantly anodic over the entire heat-affected zone. This is also evident by the corrosion attack on the weld specimens, for the as-welded specimens generally corrode across the entire heat affected zone. But the post-weld aged specimens corrode locally at the edge of the weld bead.

Thus, until further evidence can be accumulated, the cause of failure for the post-weld aged material is felt to be an anode-cathode relationship where the anode area is small in comparison to the cathode, much more so than for the as-welded specimens, therefore, resulting in severe local attack, which under high constant strain, results in stress-corrosion cracking.

C. Comparison of Stressing Methods

It would simplify the interpretation of stress corrosion tests if the tests could be made at a constant stress level. However, in order to maintain a constant stress on a test specimen whose cross sectional area decreases during exposure, due either to corrosion or to cracking, it would be necessary to continually reduce the load in proportion to the decrease in net area as well as to make allowance for stress concentrations resulting from localized corrosion or cracking. A "computorized" fixture would be needed to accomplish these requirements, and therefore, it seems impractical to consider a "constant stress" fixture for use in routine laboratory tests.

Constant Load vs Constant Deformation - Tension

The extent to which tension fixtures, both constant deformation and constant load, maintain a constant stress on the net section throughout a stress corrosion test will depend on the stiffness of the fixture, as well as the frequency and depth of cracking or localized corrosion. For instance, under some conditions, small cracks may occur at numerous locations whereas in other cases cracking may be relatively localized. Welded specimens generally fall into the latter category because stress corrosion cracks invariably occur in the very localized fusion zone.

An analysis was made to study the effect of fixture stiffness and frequency of cracking on the average stress level during stress-corrosion cracking. A stress history was calculated for plain sheet-type tensile specimens having a 1/8" x 1/2" cross section and a 5" long test section. The analysis considered only the average stresses with no allowance for stress concentration due to corrosion or cracking.

Two frequencies of cracking were assumed in the analysis. In the first case, cracking was assumed to occur at numerous closely spaced sites, and the cracks were assumed to initiate simultaneously from only one surface and to propagate at the same rate. Thus the cross-sectional area was considered to decrease uniformly along the entire gauge length. The second case was for a single crack. In order to perform the calculations it was necessary to assume a length of specimen affected by the crack. This length was assumed to be 0.1 in. The specimens were considered to be loaded initially to 46 ksi tension, which is 75% of the yield strength of X7106-T6 alloy.

Under dead load the average stress on the net section through a crack or cracks, for a specimen undergoing either localized or generalized cracking, will increase as the cross sectional area decreases. Finally, the stress will reach the tensile strength of the material, at which point the specimen will fracture mechanically. For the other extreme of constant deformation loading with an infinitely stiff fixture, the relationship between average stress on the net section and the decrease in cross sectional area will depend on the frequency of cracking: With general cracking, the stress will remain constant, whereas for localized cracking, the stress will increase markedly. The relationships between stress and reduction in area on the section through the crack for the cases discussed above are shown in Figure 50.

The stiffness of the constant-deformation fixture (Figure 35) was calculated to be 2×10^6 lb./in. while calibration tests show the constant load fixture (Figure 37) to have stiffness of 1.3×10^4 lb./in. Figure 50 shows the extent to which the two fixtures approach the assumed conditions of loading, that is, constant deformation and constant load. With general cracking the constant-deformation fixture will maintain an essentially constant average stress on the net section while the constant load fixture will cause a steadily increasing stress; this, however, never quite reaches the stress obtained under dead load conditions. With localized cracking there is very little difference in the average stress on the net section for the two fixtures. In the present example, the average stress on the net seotion for the case of localized cracking would reach the tensile strength when cracking had reduced the cross sectional area by 33 per cent in the constant load fixture and by 47 per cent in the constant deformation fixtures.

The test results, shown in Table XIII for post-weld aged X7106-T6 and X7139-T6, appear to confirm the foregoing analysis in that times to failure for the case of localized cracking are similar for specimens stressed in direct tension under conditions of constant deformation and constant load. Unfortunately, there are not test data available for making a comparison of the two loading fixtures under conditions of general cracking.

Bending vs Tension - Constant Deformation

Calculations were made to evaluate the stresses and the load required to maintain a constant deflection of a beam-type specimen, in much the same manner as was done in the case of direct-tension loading. The analysis was made for a specimen having a 1" x 1" cross section and loaded as a beam as shown in Figure 51. The beam material was assumed to have the same stress-strain relationship as that used for the calculations on the direct tension specimens. Cracking was assumed to occur on a single plane at the mid-length of the beam and the length of beam on the net section through the plane of the crack was assumed to be 0.1 in.

The analysis was made as follows: The specimen was assumed to be initially stressed to 46 ksi (75 per cent of the yield strength of X7106-T6) at the extreme fiber in the mid-span of the beam. The bolt tension (end reactions) and the beam deflection on the transverse section through the bolt axis required to produce this stress were calculated. Next, the bolt force required to maintain a constant beam deflection was determined for various depths of crack.

Test specimens may be loaded in the bending fixture (Figure 31) so that, initially, at least, the extreme fiber tensile stress in the center span of the beam is equal to the average stress in a specimen loaded in direct tension. Thus, it would seem that since the conditions of a crack initiation are similar in the two types of loading, observed differences (Table XIII) are governed by the crack propagation. Figure 51 shows a greater load relaxation accompanying crack growth in bending than in tension. In the tension test a mechanical fracture will occur when the crack depth is sufficient to produce an average stress on the net section equal to the breaking strength. However, in the bend test, only the fibers in the vicinity of the crack tip are stressed to the breaking strength so that failure would tend to occur progressively rather than suddenly. Another factor that must be recognized is that a crack produces high stress and strain concentrations and that even for applied stresses below the yield strength, a plastic stress-strain state will exist at the crack tip. Photoelastic tests* have shown that the stress and strain concentration for a given applied stress is greater in tension than in bending. Therefore, since for a given applied tensile stress the potential energy is greater in a uniform tension stress field than in a bending stress field, it seems reasonable that for localized cracking the time to fracture would be less in tension than in bend tests. Additional studies will be required to obtain a more complete understanding of the fracture mechanics of both this case and that of generalized cracking.

Residual Tension Stress

In general, the technique employed to produce residual stresses in the H-plate specimen resulted in a lower magnitude of residual stress than was anticipated. While this was a disappointment as far as stress corrosion tests were concerned, it was encouraging from the overall viewpoint that the residual stresses during welding would generally be relatively low (below 15 ksi for 1/8" sheet) for the

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* R. E. Peterson, "Stress Concentration Design Factors," John Wiley and Sons, Inc., New York, 1953.

Al-Zn-Mg alloys even when welded under restraint. Therefore, the width of the strut was decreased from 4" to 2" after welding to increase the stress level another 5 to 8 ksi. Stresses were determined from Berry strain gauge readings made before welding and after reducing the strut width to 2". The average stresses developed across the strut of the H-plate specimens are presented in Table XVI and show a range of 6.8 to 17.8 ksi for 1/8", 11.7 to 25.4 ksi for 3/8" and 22.8 to 40.5* ksi for 1" thick plate.

CONCLUSIONS:

The following conclusions are based upon stress corrosion tests in progress from 2 to 5 1/2 months and should be considered tentative at this time.

1. The general resistance to corrosion of the parent Al-Zn-Mg alloys was good; however, in the as-welded condition all four alloys suffered a similar degree of accelerated localized corrosion of the heat affected zone. This selective attack of the heat affected zone was almost completely eliminated by the post-weld aging treatment.

2. All four Al-Zn-Mg alloys - X7002, X7106, 7039 and X7139 - showed very good resistance to stress-corrosion cracking in the as-welded condition when stressed as high as 75% of their weldment yield strength regardless of the method of loading.

3. Post-weld aging (8 hours at 225°F + 16 hours at 300°F) increased the weld strength of the Al-Zn-Mg alloys but resulted in a pronounced decrease in resistance to stress-corrosion cracking. Alloys X7106 and X7139 welded with X5180 had the shortest failure times; 7039 welded with 5183 was next and X7002 welded with X5180 has not failed to date.

*Note in Table regarding question of stresses.

4. The resistance to stress-corrosion cracking of X7106 alloy plate-to-forging combinations was similar to that of plate; however, failures were predominantly on the forging side. The addition of a protective paint system delayed failure but did not prevent stress-corrosion cracking from occurring.

5. Similar stress corrosion performance was observed for 3/8" thick X7106-T6351 plate welded with X5180 alloy filler by the two welding methods, DCSP-TIG and DCRP-MIG.

6. Loading by tension or by bending rated the alloys in the same order thus far; however, failure times were shorter for the tension tests.

7. As a result of severe localized corrosion of the heat affected zone of as-welded specimens, both constant deformation and constant load fixtures have produced failure which are questionable as to whether they are mechanical or stress corrosion. A detailed examination of these failures is in progress.

STATUS:

All originally scheduled stress corrosion tests are in progress. The alternate immersion portion of this phase will be terminated after a 6 months' exposure. It is intended to continue the atmospheric tests for a minimum of 1 year's exposure.

Additional tests employing both bead on and bead off specimens will be initiated. Tests will also be conducted on 2219-T87 and 2014-T6 alloys similar to those performed on the Al-Zn-Mg alloys.

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APPENDIX A

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TABLE I

CONTROL TEST DATA OBTAINED ON ELEVEN ITEMS OF 2.5"
DIAMETER ROLLED ROD

Alloy	Composition - Per Cent (1) Cu	Fe	Si	Mn	Mg	Zn	Ni	Cr	Ti	Be	Zr	V
2014-T651	4.41	0.26	0.88	0.82	0.57	0.04	0.01	0.01	0.02	-----	----	----
2024-T351, -T851 (2)	4.54	0.22	0.11	0.57	1.57	0.02	0.00	0.00	0.03	0.000	----	----
2219-T62, -T851, -T87 (2)	6.28	0.18	0.11	0.29	0.01	0.03	0.02	0.01	0.06	-----	0.17	0.10
X7006-T651	0.05	0.14	0.06	0.20	2.11	3.99	0.00	0.11	0.05	0.000	----	----
7079-T651	0.64	0.23	0.10	0.20	3.48	4.59	0.01	0.15	0.03	0.001	----	----
7075-T651	1.61	0.19	0.10	0.02	2.50	5.86	0.00	0.19	0.05	0.001	----	----
7075-T7351	1.54	0.21	0.10	0.02	2.35	5.68	0.00	0.19	0.04	0.001	----	----
7178-T651	1.97	0.16	0.10	0.02	2.60	6.72	0.00	0.20	0.01	0.001	----	----

Alloy	Longitudinal Properties(3) T.S. ksi	Y.S. ksi	El. (% in 4D)	Solution Potential (4) -mv	Electrical Conductivity % IACS	Type of Attack (MIL-H-6088)(5) Surface	Interior
2014-T651 (6)	69.5	64.0	11.0	792	----	P	P
2024-T351	64.3	47.9	22.5	700	----	I + P	P + I
2024-T851	67.5	62.0	10.5	828	----	P	P
2219-T62	60.5	41.0	11.0	806	----	P	P
2219-T851	64.5	47.5	12.0	812	----	P	P
2219-T87 (6)	67.0	55.0	13.0	792	----	P + SI	P
X7006-T651 (6)	64.9	59.5	16.0	---	----	P	P
7079-T651 (6)	78.1	73.4	12.0	---	----	P	P
7075-T651	84.2	77.5	13.3	---	32.0	P	P
7075-T7351 (6)	76.6	68.0	13.2	---	40.6	P	P
7178-T651 (6)	92.4	85.5	11.0	---	33.2	P	P

Notes:
(1) Obtained quantometrically on Cast Disk Samples.
(2) Originated from same ingot source.
(3) Obtained at fabricating works using 1/2" diameter bars taken midway between surface and center, parallel to the rolling direction.
(4) Average steady potential value in NaCl-H_2O_2 solution, referred to 0.1 N Calomel cell at 25°C (for most alloys steady state is reached within 1/2 hour).
(5) P - Pitting, SI - Slight Intergranular, I - Intergranular.
(6) These six alloys tested in atmospheres; others tested only in alternate immersion.

TABLE II

ATMOSPHERIC STRESS-CORROSION DATA ON 1/8" DIAMETER TRANSVERSE TENSILE BARS
MACHINED FROM 2.5" DIAMETER ROLLED ROD

Exposure Date: 1-3-64 Point Comfort, Texas

S. No.	Alloy	Unstressed Dash No.	Unstressed Exp. (Mos.)	Unstressed % Loss T.S.	Stressed Stress Level	Stressed Dash No.	Stressed Days to Fail
302309	2014-T651	T19	1	7	75% Y.S.	T24	40
		T20	2	6	75% Y.S.	T25	40
		T21	8.5	12	75% Y.S.	T26	45
		T22	12*	12	50% Y.S.	T27	137
		T23			50% Y.S.	T28	96
					50% Y.S.	T29	96
					50% Y.S.	T30	508
					25% Y.S.	T31	
					25% Y.S.	T32	
					25% Y.S.	T33	
302353	2219-T87	T14	1	6	75% Y.S.	T19	
		T15	2	9	75% Y.S.	T20	
		T16	8.5	11	75% Y.S.	T21	
		T18	12*	18	75% Y.S.	T22	
		T17			75% Y.S.	T23	
302507	X7006-T651	T19	1	0	75% Y.S.	T24	104
		T20	2	0	75% Y.S.	T25	40
		T21	7	0	75% Y.S.	T26	151
		T22	12*	0	50% Y.S.	T27	151
		T23			50% Y.S.	T28	
					50% Y.S.	T29	
					50% Y.S.	T30	
					25% Y.S.	T31	
					25% Y.S.	T32	
					25% Y.S.	T33	
302354	7079-T651	T19	1	2	75% Y.S.	T24	88
		T20	2	0	75% Y.S.	T25	59
		T21	7	8	75% Y.S.	T26	79
		T22	12*	7	50% Y.S.	T27	137
		T23			50% Y.S.	T28	137
					50% Y.S.	T29	165
					50% Y.S.	T30	137
					25% Y.S.	T31	
					25% Y.S.	T32	
					25% Y.S.	T33	
302599	7075-T7351	T14	1	0	75% Y.S.	T19	
		T15	2	0	75% Y.S.	T20	
		T16	8.5	6	75% Y.S.	T21	
		T17	12*	8	75% Y.S.	T22	
		T18			75% Y.S.	T23	
302308	7178-T651	T19	1	4	75% Y.S.	T24	79
		T20	2	5	75% Y.S.	T25	40
		T21	7	10	75% Y.S.	T26	79
		T22	12*	10	50% Y.S.	T27	96
		T23			50% Y.S.	T28	165
					50% Y.S.	T29	88
					50% Y.S.	T30	104
					25% Y.S.	T31	
					25% Y.S.	T32	
					25% Y.S.	T33	

Exposure Date: 12-8-63 Point Judith, Rhode Island

S. No.	Alloy	Unstressed Dash No.	Unstressed Exp. (Mos.)	Unstressed % Loss T.S.	Stressed Stress Level	Stressed Dash No.	Stressed Days to Fail
302309	2014-T651	T34	1	12	75% Y.S.	T39	56
		T35	2.5	11	75% Y.S.	T40	56
		T36	7.5	21	75% Y.S.	T41	49
		T37	14*	25	50% Y.S.	T42	56
		T38			50% Y.S.	T43	252
					50% Y.S.	T44	548
					50% Y.S.	T45	161
					25% Y.S.	T46	
					25% Y.S.	T47	
					25% Y.S.	T48	
302353	2219-T87	T24	1	7	75% Y.S.	T29	
		T25	2.5	10	75% Y.S.	T30	
		T26	7.5	18	75% Y.S.	T31	
		T28	14*	23	75% Y.S.	T32	
		T27			75% Y.S.	T33	
302507	X7006-T651	T34	1	0	75% Y.S.	T39	280
		T35	2.5	0	75% Y.S.	T40	304
		T36	7.5	6	75% Y.S.	T41	304
		T37	14*	5	50% Y.S.	T42	304
		T38			50% Y.S.	T43	280
					50% Y.S.	T44	304
					50% Y.S.	T45	
					25% Y.S.	T46	
					25% Y.S.	T47	
					25% Y.S.	T48	
302354	7079-T651	T34	1	8	75% Y.S.	T39	27
		T35	2.5	7	75% Y.S.	T40	56
		T36	7.5	14	75% Y.S.	T41	27
		T37	14*	15	50% Y.S.	T42	49
		T38			50% Y.S.	T43	27
					50% Y.S.	T44	27
					50% Y.S.	T45	27
					25% Y.S.	T46	
					25% Y.S.	T47	
					25% Y.S.	T48	
302599	7075-T7351	T24	1	2	75% Y.S.	T29	
		T25	2.5	11	75% Y.S.	T30	
		T26	7.5	8	75% Y.S.	T31	
		T27	14*	10	75% Y.S.	T32	
		T28			75% Y.S.	T33	
302308	7178-T651	T34	1	9	75% Y.S.	T39	49
		T35	2.5	13	75% Y.S.	T40	27
		T36	7.5	18	75% Y.S.	T41	27
		T37	14*	16	50% Y.S.	T42	90
		T38			50% Y.S.	T43	208
					50% Y.S.	T44	76
					50% Y.S.	T45	49
					25% Y.S.	T46	
					25% Y.S.	T47	
					25% Y.S.	T48	

Exposure Date: 11-11-63 New Kensington, Pennsylvania

S. No.	Alloy	Unstressed Dash No.	Unstressed Exp. (Mos.)	Unstressed % Loss T.S.	Stressed Stress Level	Stressed Dash No.	Stressed Days to Fail
302309	2014-T651	T49	1	0	75% Y.S.	T54	205
		T50	2	3	75% Y.S.	T55	
		T51	7	8	75% Y.S.	T56	
		T52	12*	9	50% Y.S.	T57	
		T53			50% Y.S.	T58	
					50% Y.S.	T59	
					50% Y.S.	T60	
					25% Y.S.	T61	
					25% Y.S.	T62	
					25% Y.S.	T63	
302353	2219-T87	T35	1	1	75% Y.S.	T40	
		T36	2	0	75% Y.S.	T41	
		T37	7	5	75% Y.S.	T42	
		T38	12*	3	75% Y.S.	T43	
		T39					
302507	X7006-T651	T49	1	5	75% Y.S.	T54	156
		T50	2	0	75% Y.S.	T55	155
		T51	7	1	75% Y.S.	T56	177
		T52	12*	0	50% Y.S.	T57	223
		T53			50% Y.S.	T58	205
					50% Y.S.	T59	259
					50% Y.S.	T60	164
					25% Y.S.	T61	
					25% Y.S.	T62	
					25% Y.S.	T63	
302354	7079-T651	T49	1	0	75% Y.S.	T54	98
		T50	2	0	75% Y.S.	T55	98
		T51	7	7	75% Y.S.	T56	116
		T52	12*	2	50% Y.S.	T57	172
		T53			50% Y.S.	T58	192
					50% Y.S.	T59	197
					50% Y.S.	T60	126
					25% Y.S.	T61	
					25% Y.S.	T62	
					25% Y.S.	T63	
302599	7075-T7351	T34	1	1	75% Y.S.	T39	
		T35	2	0	75% Y.S.	T40	
		T36	7	4	75% Y.S.	T41	
		T37	12*	0	75% Y.S.	T42	
		T38			75% Y.S.	T43	
302308	7178-T651	T49	1	0	75% Y.S.	T54	192
		T50	2	3	75% Y.S.	T55	198
		T51	7	7	75% Y.S.	T56	192
		T52	12*	6	50% Y.S.	T57	258
		T53			50% Y.S.	T58	219
					50% Y.S.	T59	258
					50% Y.S.	T60	258
					25% Y.S.	T61	
					25% Y.S.	T62	
					25% Y.S.	T63	

Note: * To be tested whenever tests on stressed specimens are concluded.

TABLE III

SALT SPRAY STRESS CORROSION DATA ON 1/8" DIAMETER TRANSVERSE TENSILE BARS

Part A

Acidified 5% NaCl Intermittent Spray - Two Weeks

Alloy	Number of Failures and Time to Failure						% Loss in T.S. Due to Corrosion				
	Str. 75%Y.S.		Str. 50%Y.S.		Str. 25%Y.S.		Str. 75%Y.S.	Str. 25%Y.S.	Unstressed		
	F/N	Days	F/N	Days	F/N	Days	2 Weeks	2 Weeks	3 Days	1 Week	2 Weeks
7079-T651	3/3	3,3,3	3/3	3,3,6	0/3	OK 14	-------	-------	20	24	34
X7006-T651	3/3	1,3,3	3/3	3,4,5	0/3	OK 14	-------	-------	0	9	14
2014-T651	3/3	2,2,2	3/3	2,3,3	1/3	10	-------	51	22	25	32
7178-T651	---	-----	3/3	4,5,5	0/3	OK 14	-------	40	15	23	34
2219-T87	0/3	OK 14	---	-----	---	-----	39	-------	16	25	37
7075-T7351	0/3	OK 14	---	-----	---	-----	39	-------	16	23	35

Part B

Neutral 5% NaCl Continuous Spray - Four Weeks

Alloy	Number of Failures and Time to Failure						% Loss in T.S. Due to Corrosion				
	Str. 75%Y.S.		Str. 50%Y.S.		Str. 25%Y.S.		Str. 75%Y.S.	Str. 25%Y.S.	Unstressed		
	F/N	Days	F/N	Days	F/N	Days	4 Weeks	4 Weeks	1 Week	2 Weeks	4 Weeks
7079-T651	---	-----	0/3	OK 28	0/3	OK 28	-------	-------	0	1	0
X7006-T651	---	-----	1/3	(*)	0/3	OK 28	-------	-------	0	0	0
2014-T651	3/3	(*)	1/3	(*)	0/3	OK 28	-------	16	6	9	12
7178-T651	---	-----	0/3	OK 28	0/3	OK 28	-------	5	1	3	4
2219-T87	0/3	OK 28	---	-----	---	-----	14	-------	4	8	15
7075-T73	0/3	OK 28	---	-----	---	-----	2	-------	0	3	4

Note: (*) Failures found at end of test while dismantling specimens.

TABLE IV

PROTECTIVE SURFACE TREATMENTS EVALUATED

System No.	System
1	As machined - control
2	Shot peened
3	Metallized with 7072 aluminum alloy (three pass system with average thickness of 5 mil and maximum of 7 mil).
4	Zinc electroplate (3 to 4 mil).
5	Alumilite 205 (0.2 mil)
6	Modified Alumilite 226 (2 mil)
7	Alodine 1200 plus Zinc Chromate Primer (0.5 mil)
8	Alodine 1200 plus Epoxy-Polyamide (2 mil)
9	Alodine 1200 plus Strontium Chromate Epoxy Primer (1 mil) plus Epoxy-Polyamide (2 mil)
10	Alodine 1200 plus Strontium Chromate Epoxy Primer (1 mil) plus Epoxy-Polyamide Vehicle with added aluminum pigment (1 mil) plus Epoxy-Polyamide (2 mil)
11	Alodine 1200 plus Polyurethane Pigmented with Titanium Dioxide (2 mil)
12	Alodine 1200 plus Strontium Chromate Epoxy Primer (1 mil) plus Polyurethane Pigmented with Titanium Dioxide (2 mil)
13	Zinc-rich paint (Epoxy-Polyamide Pigmented with Zinc) (3 mil)
14	Shot peened plus Alodine 1200 plus Strontium Chromate Epoxy Primer (1 mil) plus Epoxy-Polyamide (2 mil)
15	Metallized with 7072 aluminum alloy (three pass system with average thickness of 5 mil and maximum of 7 mil) plus Alodine 1200 plus Strontium Chromate Epoxy Primer (1 mil) plus Epoxy-Polyamide (2 mil)

TABLE V

CORROSION TEST SCHEDULE FOR PROTECTED SPECIMENS
NUMBER OF SPECIMENS PER SURFACE TREATMENT PER ENVIRONMENT
UNSTRESSED = 1/2" DIAMETER LONGITUDINAL TENSILE BAR
STRESSED (75% TRANSVERSE Y.S.) = 2 1/4" O.D. x 1/8" WALL TRANSVERSE RING

Alloy	Original Properties	3.5% NaCl Alternate Immersion		Seacoast Atmosphere				Industrial Atmosphere		Total for 15 Treatments (1)	
				Point Comfort Texas		Point Judith Rhode Island		New Kensington Pennsylvania			
	Bars	Bars	Rings	Bars	Rings	Bars	Rings	Bars	Rings	Bars	Rings
2014-T651	3	3	5	3	10 (2)	3	5	3	10 (2)	183	450
7079-T651	3	3	5	3	10 (2)	3	5	3	10 (2)	183	450
2219-T87 (3)	3	3	5	3	5	-	-	-	-	93	10
7075-T7351 (3)	3	3	5	3	5	-	-	-	-	93	10
2024-T351	3	3	5	-	-	-	-	-	-	48	75
7178-T651	3	3	5	-	-	-	-	-	-	48	75
Sub Total 1 Treatment	18	18	30	12	30	6	10	6	20	-	-
Total 15 Treatments	18	270	310	180	310	90	150	90	300	648	1070

Notes:
(1) Consists of 1 set of unprotected control plus 14 sets of protected specimens.
(2) Includes 5 additional specimens with intentionally damaged coatings.
(3) Stressed ring specimens exposed only in unprotected condition.

TABLE VI

PER CENT LOSS IN TENSILE STRENGTH AND ELONGATION OBTAINED ON TRIPLICATE 1/2" DIAMETER LONGITUDINAL TENSILE BARS WITH VARIOUS PROTECTIVE COATINGS EXPOSED TO 3.5% NaCl ALTERNATE IMMERSION

PERIOD OF EXPOSURE: SYSTEM 1 & 2 = 6 MONTHS, ALL OTHERS = 1 YEAR

Protective System		Per Cent Decrease by Corrosion, Range	
Number	Description	Tensile Strength	Elongation
1 (*)(Δ)	As-machined control	1-5	12-43
2 (*)	Shot peened	0-6	20-50
3 (Δ)	7072 metallized	0-2	5-54
4	Zinc electroplate	0-13	15-74
5 (Δ)	Alumilite 205	0-2	0-5
6	Alumilite 226	0-2	0-8
7	Zinc chromate primer	0-2	0-7
8 (Δ)	Epoxy polyamide	0-1	0-8
9	Primer + epoxy	0-1	0-18
10	Primer + epoxy with Al pigment + epoxy	0	0-17
11	Polyurethane	0-2	0-15
12	Primer + polyurethane	0	0-30
13 (Δ)	Zinc rich paint	0	0-25
14	Shot peen + primer + epoxy	0-1	3-53
15	7072 metallized + primer + epoxy	0-1	7-43

Notes: (1) Alloys evaluated were: 2024-T351, 2014-T651, 2219-T87, 7079-T651, 7178-T651 and 7075-T7351.

(*) These systems tested after 6 months' exposure.

(Δ) The per cent loss in tensile properties for individual alloys are shown in Figures 7-11.

TABLE VII

3.5% NaCl ALTERNATE IMMERSION TESTS ON PROTECTED 2-1/4" O.D. RINGS STRESSED 75% Y.S. - DAYS TO FAILURE

		Exposure Times as of 6-30-65 =	627	606	596	616	627	611	627	621	615	600	592	585	627	574	574
		Exposure Date (all 1963) =	10-11	11-1	11-11	10-22	10-11	10-27	10-11	10-17	10-23	11-7	11-15	11-22	10-11	12-3	12-3
		Protective System No. =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Alloy	**S. No.**	**R. No.**															
2024-T351	302210	1	16	18				7	23	472					505		
		2	23	31				7	30	459					549		
		3	13	31			409	7	61								
		4	14	24			19	7	35						289		
		5	21	35			410	7	21						354		
2014-T651	302309	1	6	13				2	11								
		2	3	13				2	15				71		354		
		3	4	12		612		2	19				211		322		
		4	6	13				2	18				67		169		
		5	4	14				2	18				58		409		
7079-T651	302354	1	14	80		315	1	162	115			23			240		
		2	16	152		584	1	177	190			263	8		27		
		3	17	406		351	1	9	4	242			21	123	173		327
		4	14	520	37	309	1		46					50	21		
		5	10	60		584	1		151						67		
7178-T651	302308	1	17	131		270	352	3	39				4		127		
		2	15	193		238	302	6	104						170		
		3	16	120		37		3	32						149		
		4	17	141			102	8	63			327	10	215	132		
		5	17	107		473	325	6	59				432		115		
2219-T87	302353	1	*														
		2															
		3															
		4	*														
		5															
7075-T7351	302599	1	553														
		2	553														
		3	553														
		4	553														
		5	446														

Tests Conducted Only on System 1, (Bare Control).

Note: (*) Did not fail but removed from test after 565 days for microscopic examination.

TABLE VIII

ATMOSPHERE STRESS-CORROSION TESTS ON PROTECTED 2-1/4" O.D. RINGS, STRESSED 75% Y.S. - DAYS TO FAILURE

Environment (Exposure Date)	Alloy (S. No.)	Specimen Condition	Ring No.	Protective Systems 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
New Kensington (12-6-63)	2014-T651 (302309)	Undamaged	21	91				103	45									
			22	124				129	28									
			23	167				180	73									
			24	117				124	73									
			25	73				285	90									
		Damaged+	26	--				124	138		167	270		167	493	437		
			27	--				125	45		185	125	229	194				
			28	--				96	35			138	90	198				
			29	--				63	101	147	171	167	68	147	171			
			30	--				514	167			138	194	194				
	7079-T651 (302354)	Undamaged	21	54				28	73	129	215		318		336			
			22	76				28	59	203	180			111		*		
			23	35				31	54	59		539						198
			24	45				35	54	157		5		222				
			25	68				21	62	222		546	173		117			
		Damaged	26	--				18	96	171	129	117	54	48	68			
			27	--				35	*	229	14	73	54	33	151	571		
			28	--				63	73	270	91	151	77	59	105	157		
			29	--			18	20	63	151	111	160	157	59	157	157		
			30	--		325		35	63	383	*	229	45	33	124	262		
Point Judith (12-21-63)	2014-T651 (302309)	Undamaged	16	14	63			14	43	43				63				
			17	14	112			56	43	43		316		43				
			18	14	240			43	43					117		91		
			19	14	240			56	43	91	240			63				
			20	14	112			63	43	43	477	423		91		77		
	7079-T651 (302354)	Undamaged	16	36				14	*		291		70	423				43
			17	43			477	36	43	240	240		240	291				
			18	43			330	14	91	70	146		240	112	146	112		
			19	36				14	43	56	267			477	240			
			20	43				36	43	70	112			112		140		
Point Comfort (1-3-64)	2014-T651 (302309)	Undamaged	6	7				151	35	124								
			7	35				130	35					117				
			8	35				117	35	79				130				
			9	7					11									
			10	35				124	11	79				124				
		Damaged	11	--				383	35	79	45	45	87	70	79	111		
			12	--				111	35	315	70	59	70	70	70			
			13	--				130	35	104	35	70	59	70	79	124		
			14	--				111	7		70	59	59	59	79			
			15	--					35	117	59	70	79	70	70	124		
	7079-T651 (302354)	Undamaged	6	87		187		*	124			200		96	35			
			7	7				35	79		179	158	7					
			8	59				7	35		179		7		11			
			9	35		40	320	7	130		124			35	11			
			10	35			515	11	145		35			35				
		Damaged	11	--				7	35		111	137	111	35	158			
			12	--				35	137	35	*	165	111	35	124	59		
			13	--				11	35	45	111	179	151	59	130			
			14	--				7	130		*	187	124	45	40			
			15	--				35	7	208	124	165	173	7	96	*		
	2219-T87 (302353)	Undamaged		System 1 Only			R6-	R7-		R8-		R9-		R10-				
	7075-T7351 (302599)	Undamaged		System 1 Only			R6-	R7-		R8-		R9-		R10-				

* Failed prior to exposure.

Note: Exposure times as of 6-30-65: New Kensington 571 days, Point Judith 556 days and Point Comfort 543 days.

\+ Coating intentionally damaged by machining a peripheral scribe mark along the center line of the 2" width extending through the coating and to a depth of 2 mils ± 1 mil into the underlying metal.

TABLE IX

SUMMARY COMPARISON OF THE EFFECTIVENESS OF THE VARIOUS PROTECTIVE TREATMENTS

Part A

2014-T651 and 7079-T651 Specimens Exposed to All Four Environments

	Number of Failures								
	2014-T651			7079-T651			Both Alloys		
System	Undamaged (20 Specs.)	Damaged (10 Specs.)	Total (30 Specs.)	Undamaged (20 Specs.)	Damaged (10 Specs.)	Total (30 Specs.)	Undamaged (40 Specs.)	Damaged (20 Specs.)	Total (60 Specs.)
14 - shot peen + epoxy	0	0	0	0	0	0	0	0	0
15 - 7072 metallized + epoxy	0	0	0*	3	0	3	3	0	3
3 - 7072 metallized	0	0	0*	3	1	4	3	1	4
4 - Zn electroplate	1	0	1*	9	1	10	10	1	11
2 - shot peen	10	0	10	5	0	5*	15	0	15
13 - Zn rich paint	7	4	11	8	6	14	15	10	25
12 - primer + polyurethane	0	7+	7*	9	10+	19	9	17+	26
9 - primer + epoxy	2	10+	12	5	10+	15	7	20+	27
10 - primer + Al pigmented epoxy + epoxy	0	9+	9*	9	10+	19	9	19+	28
8 - epoxy	2	8+	10*	12	10+	22	14	18+	32
7 - Zinc chromate	12	5	17	14	8	22	26	13	39
11 - polyurethane	12	10+	22	12	10+	22	24	20+	44
5 - Alumilite 205	14	9	23	20	10	30	34	19	53
6 - Alumilite 226	20	10	30	18	10	28	38	20	58
1 - as machined control	20	--	20	20	--	20	40	--	40

Notes: (*) Protective system appreciably better on asterisked alloy than on other alloy.
(+) Effectiveness of this system greatly reduced by mechanical damage marks.

Part B

2024-T351, 2014-T651, 7079-T651 and 7178-T651 Alloys - All Specimens, All Environments

F/N = Number of Failures/Number of Specimens

Group A System	Group A F/N	Group B System	Group B F/N	Group C System	Group C F/N
14	0/70	4	16/70	13	34/70
15	3/70	2	25/70	8	34/70
3	4/70	9	27/70	11	47/70
		12	27/70	7	49/70
		10	29/70	5	60/70
				6	68/70

Rating: A = Most recommended systems.
B = Recommended for restricted types of applications.
C = Not recommended.

TABLE X

RESULTS OF PRELIMINARY STRESS-CORROSION CRACKING TESTS OF HIGHLY STRESSED SHEET SPECIMENS OF 2219-T37 ALLOY EXPOSED TO VARIOUS ELECTROLYTES BY ALTERNATE IMMERSION

Electrolyte	Concentration, g/1			pH	Days to Failure
	NaCl	CrO_3	$K_2Cr_2O_7$		
Standard	35.0	----	----	7.2	5, 5, 5
A	28.1	0.5	0.5	2.3	27, 27
B	40.3	3.3	3.3	1.5	1, 2
C	40.6	13.9	0.2	0.9	1, 2
D	47.6	0.2	2.9	2.7	16, OK 30
E	61.8	2.9	3.4	1.5	2, 2
F	25.0	3.4	6.1	1.0	1, 1
G	38.9	6.1	13.9	1.0	1, 1
H	3.0	30.0	30.0	0.7	1, 1
I	45.0	1.0	----	1.1	3, 3

Notes: (1) Test specimens were formed from 0.064" thick sheet and sprung into fixtures holding them at a stress greater than the proportional limit of the material. (Refer to Figure 3 in Reference 10.)

TABLE XI

STRESS-CORROSION OF 2219 ALLOY IN SEVERAL ELECTROLYTES
TRANSVERSE TENSILE BARS MACHINED FROM 2.5" DIAMETER ROLLED ROD GIVEN VARIOUS AGING TREATMENTS

Aging of -T37 Material	3.5% NaCl - 84 Days Str. 75% Y.S. Days to Failure	 Str. 75% Y.S. % Loss T.S.	 Unstr. % Loss T.S.	 % Stress Corrosion	Solution F - 30 Days Str. 75% Y.S. Days to Failure	 Str. 75% Y.S. % Loss T.S.	 Unstr. % Loss T.S.	 % Stress Corrosion	Solution G - 30 Days Str. 75% Y.S. Days to Failure	 Str. 75% Y.S. % Loss T.S.	 Unstr. % Loss T.S.	 % Stress Corrosion	Solution H - 30 Days Str. 75% Y.S. Days to Failure	 Str. 75% Y.S. % Loss T.S.	 Unstr. % Loss T.S.	 % Stress Corrosion
None (53-39)△	1 (2)* 1 (2) 2 3	-- -- -- --	12 12 19 27	74 74 58 41	1 -- 2 --	-- -- -- --	3 -- 47 --	94 -- 0 --	0.25 -- 0.25 --	-- -- -- --	13 -- 8 --	72 -- 83 --	0.12 -- 0.12 --	-- -- -- --	0 -- +3 --	100 -- 100 --
3 hr./325°F (66-50)	1 (2) 2 (2)	-- --	16 25	63 42	1 2	-- --	2 0	95 100	1 1	-- --	1 5	98 89	0.17 0.17	-- --	2 +1	96 100
6 hr./325°F (68-53)	1 (3) 2 (3)	-- --	10 15	76 63	2 3	-- --	2 0	95 100	1 1	-- --	0 4	100 90	0.21 0.21	-- --	4 1	90 98
8 hr./325°F (70-56)	4 (5) 4 (5)	-- --	14 17	65 57	4 7	-- --	4 5	90 87	1 3	-- --	2 7	95 82	1 1	-- --	11 10	72 75
10 hr./325°F (71-57)	3 (8) 3 (OK 84)	-- --	10 13	75 67	4 10	-- --	0 10	100 74	3 3	-- --	4 3	90 93	1 1	-- --	10 8	75 80
12 hr./325°F (69-56)	9 (OK 84) 24 (OK 84)	-- --	19 15	51 61	7 14	-- --	1 6	97 84	4 7	-- --	2 2	95 95	1 1	-- --	3 4	92 90
14 hr./325°F (71-58)	23 (OK 84) OK 84(OK 84)	-- 34	22 21	43 38	14 15	-- --	7 5	82 87	7 9	-- --	10 6	74 84	1 1	-- --	12 8	69 79
20 hr./325°F (70-56)	49 (OK 84) 77 (OK 84)	-- --	25 32	37 20	OK 30 OK 30	22 22	12 7	45 68	23 22	-- --	15 18	62 55	2 2	-- --	11 8	72 80
Plant Aged -T87 (24 hr./325°F) (66-52)	OK 84(OK 84) OK 84(OK 84)	38 30	32 30	16 0	OK 30 OK 30	25 24	13 10	48 58	OK 30 OK 30	40 34	20 18	50 47	2 3	-- --	12 17	70 58

Notes: (1) Tests conducted in a closed alternate immersion cabinet with an air temperature averaging about 80-85°F and the relative humidity averaging about 40-45%.
3.5% NaCl using New Kensington tap water (Solution pH, 7.0 - 7.5).
Solution F - 2.50% NaCl + 0.34% CrO_3 + 0.61% $K_2Cr_2O_7$ using Demineralized water (Solution pH, 1.0 - 1.5).
Solution G - 3.89% NaCl + 0.61% CrO_3 + 1.39% $K_2Cr_2O_7$ using Demineralized water (Solution pH, 1.0 - 1.3).
Solution H - 0.30% NaCl + 3.00% CrO_3 + 3.00% $K_2Cr_2O_7$ using Demineralized water (Solution pH, 0.7 - 0.8).
(2) Unstressed specimens removed at approximately the same time as failed stressed specimens.
(3) Per cent stress corrosion - Jones Index.
(4) * Days to fail for a repeat test are shown in parentheses.
(5) △ Numbers in parentheses indicate the tensile strength and yield strength of the material.

TABLE XII

PART A

CHEMICAL COMPOSITIONS AND TENSILE PROPERTIES (PARENT AND WELD)
OF Al-Zn-Mg ALLOYS - X7002, X7106, 7039 AND X7139

Product	Thickness	Alloy and Temper	Plant Lot No.	Lab. S. No.	Composition - Per Cent (Remelt Analysis) Cu	Fe	Si	Mn	Mg	Zn	Cr	Ti	Zr
Sheet	0.125"	X7002-T6	643-711	320447	0.64	0.14	0.07	0.22	2.41	3.32	0.18	0.02	0.01
Plate	0.375"	X7002-T651	643-721	320448	0.64	0.14	0.07	0.22	2.41	3.32	0.18	0.02	0.01
Sheet	0.125"	X7106-T6	643-661	320444	0.05	0.14	0.08	0.25	2.24	4.01	0.09	0.03	0.10
Plate	0.375"	X7106-T6351	643-651	320445	0.05	0.14	0.08	0.25	2.24	4.01	0.09	0.03	0.10
Plate	1.00"	X7106-T6351	183-041 182-711	320446	0.05	0.14	0.08	0.25	2.24	4.01	0.09	0.03	0.10
Forging	12.0"	X7106-T6352	-------	320426	0.08	0.12	0.12	0.23	2.18	4.39	0.10	0.04	0.10
Sheet	0.125"	7039-T6	643-701	320449	0.04	0.15	0.12	0.35	2.88	4.00	0.23	0.03	----
Plate	0.375"	7039-T651	643-691	320450	0.04	0.15	0.12	0.35	2.88	4.00	0.23	0.03	----
Sheet	0.125"	X7139-T6	643-681	320451	0.05	0.11	0.06	0.34	2.88	3.89	0.16	0.03	0.09
Plate	0.375"	X7139-T6351	643-671	320452	0.05	0.11	0.06	0.34	2.88	3.89	0.16	0.03	0.09
Filler Wire (1)	1/16" Dia.	X5180	-------	------				0.50	4.00	2.00		0.10	0.15
Filler Wire (1)	1/16" Dia.	5183	-------	------	0.05			1.00	5.00	0.10	0.10	0.15	

Part B

TENSILE PROPERTIES (2)

S. No.	Thickness	Alloy and Temper	Parent Metal T.S. ksi	Parent Metal Y.S. ksi	Parent Metal El. (2") %	Filler Alloy	As Welded T.S. ksi	As Welded Y.S. ksi(3)	As Welded El. (3) %	As Welded % Joint (4) Efficiency	Post-Weld Aged T.S. ksi	Post-Weld Aged Y.S. ksi	Post-Weld Aged El. (3) %	Post-Weld Aged % Joint (4) Efficiency
320444 & A	0.125"	X7106-T6 Sheet	65.2	57.3	11.5	X5180	53.0	37.7	4.8	81	59.8	50.0	6.3	92
320451 & A	0.125"	X7139-T6 Sheet	67.2	58.8	11.8	X5180	55.1	38.1	4.8	82	61.4	50.1	6.0	91
320449 & A	0.125"	7039-T6 Sheet	67.2	57.2	11.2	5183	55.8	37.7	5.5	83	60.1	48.3	4.8	90
320447 & A	0.125"	X7002-T6 Sheet	57.8	45.2	15.0	X5180	49.4	34.7	4.5	85	53.4	44.0	4.8	92
320445 & A	0.375"	X7106-T6351 Plate	63.2	54.7	14.5	X5180	52.6	41.3	2.2	83	56.6	49.6	---	90
320445M & MA (5)	0.375"	X7106-T6351 Plate	63.2	54.7	14.5	X5180	54.3	43.3	2.0	86	56.2	48.8	2.8	89
320452 & A	0.375"	X7139-T6351 Plate	67.9	58.7	14.0	X5180	54.4	42.8	1.8	80	60.4	51.9	2.6	89
320450 & A	0.375"	7039-T651 Plate	67.8	58.6	13.0	5183	54.8	43.5	1.6	81	57.8	50.9	2.0	85
320448	0.375"	X7002-T651 Plate	61.2	49.8	15.2	X5180	49.9	37.0	1.9	82	----	----	---	--
320426S & SA	0.375"	X7106-T6352 Forging (Short Transverse)	60.6	48.5	11.5	X5180	51.5	38.6	3.3	85	50.1	43.5	2.0	82
320426S & SA	0.375"	X7106-T6352 Forging	60.6	48.5	11.5	X5180	50.2	40.0	1.8	83	53.8	44.6	---	89
320445 & A	0.375"	X7106-T6351 Plate (Short Transverse Forging)	63.2	54.7	14.5					79				85
320426L & LA	0.375"	X7106-T6352 Forging	60.0	50.6	9.0	X5180	49.9	39.7	1.8	83	56.0	49.3	2.6	94
320445 & A	0.375"	X7106-T6351 Plate (Long Transverse Forging)	63.2	54.7	14.5					79				89
320446 & A (5)	1.00"	X7106-T6351 Plate	63.2	54.6	14.5	X5180	52.0	38.3	3.0	82	54.9	49.3	2.2	87

Notes:
(1) Nominal composition.
(2) Tensile properties based on average of two x-grain specimens.
(3) Stress to produce 0.2% offset in 2" gauge length centered across weld and elongation in 2" for material 0.125" thick, stress to produce 0.2% offset in 10" gauge length centered across weld and elongation in 10" for material 0.375" and 1.00" thick.
(4) Based on comparison of weld tensile strength against parent metal tensile strength.
(5) DCRP-MIG butt welded, all others DCSP-TIG butt welded.

TABLE XIII

Part A

STRESS-CORROSION DATA ON 1/8" THICK Al-Zn-Mg SHEET ALLOYS
DCSP-TIG SQUARE BUTT WELDED IN ONE PASS

					3 1/2% NaCl - Alt. Imm. Stressed 75% Y.S.			New Kensington Atmosphere Stressed 75% Y.S.			Point Judith Atmosphere Stressed 75% Y.S.		
S. No.	Alloy and Temper	Filler Alloy	(1) Weld Condition	(2) Loading Method	Dash No.	Days to Fail	Exposure Date	Dash No.	Days to Fail	Exposure Date	Dash No.	Days to Fail	Exposure Date
320444	X7106-T6	X5180	AW	Bending - CD	1 + 2		1-18-65	5 + 6		1-20-65	9 + 10		3-6-65
				Bending - CD	3 + 4		1-18-65	7 + 8		1-20-65	11 + 12		3-6-65
				Direct Tension - CD	1		2-3-65	4		2-9-65	7		3-6-65
				Direct Tension - CD	2		2-3-65	5		2-9-65	8		3-6-65
				Direct Tension - CD	3		2-3-65	6		2-9-65	9		3-6-65
				Direct Tension - CL	10		2-8-65	13		2-12-65	16		3-28-65
				Direct Tension - CL	11	129+	2-8-65	14		2-12-65	17		3-28-65
				Direct Tension - CL	12		2-8-65	15		2-12-65	18		3-28-65
320444A	X7106-T6	X5180	PWA	Bending - CD	1 + 2*	13	2-3-65	5 + 6	83	2-12-65	9*+ 10	96	3-6-65
				Bending - CD	3 + 4		2-3-65	7 + 8		2-12-65	11 + 12		3-6-65
				Direct Tension - CD	1	5	2-2-65	4	58	2-9-65	7	96	3-6-65
				Direct Tension - CD	2	2	2-2-65	5	58	2-9-65	8	96	3-6-65
				Direct Tension - CD	3	3	2-2-65	6	45	2-9-65	9	96	3-6-65
				Direct Tension - CL	10	5	2-2-65	13	69	2-12-65	16	74	3-28-65
				Direct Tension - CL	11	4	2-2-65	14	72	2-12-65	17	74	3-28-65
				Direct Tension - CL	12	4	2-2-65	15	72	2-12-65	18		3-28-65
320451	X7139-T6	X5180	AW	Bending - CD	1 + 2		1-18-65	5 + 6		1-20-65	9 + 10		3-6-65
				Bending - CD	3 + 4		1-18-65	7 + 8		1-20-65	11 + 12		3-6-65
				Direct Tension - CD	1		2-3-65	4		2-9-65	7		3-6-65
				Direct Tension - CD	2	143	2-3-65	5		2-9-65	8		3-6-65
				Direct Tension - CD	3		2-3-65	6		2-9-65	9		3-6-65
				Direct Tension - CL	10		2-8-65	13		2-12-65	16		3-28-65
				Direct Tension - CL	11	123	2-8-65	14		2-12-65	17		3-28-65
				Direct Tension - CL	12		2-8-65	15		2-12-65	18		3-28-65
320451A	X7139-T6	X5180	PWA	Bending - CD	1 + 2*	6	2-3-65	5 + 6	87	2-12-65	9*+ 10	96	3-6-65
				Bending - CD	3 + 4		2-3-65	7 + 8		2-12-65	11 + 12		3-6-65
				Direct Tension - CD	1	2	2-2-65	4	35	2-9-65	7	96	3-6-65
				Direct Tension - CD	2	2	2-2-65	5	34	2-9-65	8	96	3-6-65
				Direct Tension - CD	3	2	2-2-65	6	21	2-9-65	9	96	3-6-65
				Direct Tension - CL	10	2	2-2-65	13	47	2-12-65	16	74	3-28-65
				Direct Tension - CL	11	2	2-2-65	14	47	2-12-65	17	74	3-28-65
				Direct Tension - CL	12	1	2-2-65	15	54	2-12-65	18	74	3-28-65

Notes: (1) AW - As Welded; PWA - Post Weld Aged 8 hours at 225°F + 16 hours at 300°F.
(2) CD - Constant Deformation; CL - Constant Load.
* Indicates the specimen that failed in the beam assembly.
\+ Mechanical failure as identified by metallographic examination.
(3) Face stressed in tension.
(4) Root stressed in tension.

Part B

STRESS-CORROSION DATA ON 1/8" THICK Al-Zn-Mg SHEET ALLOYS
DCSP-TIG SQUARE BUTT WELDED IN ONE PASS

					3 1/2% NaCl - Alt. Imm. Stressed 75% Y.S.			New Kensington Atmosphere Stressed 75% Y.S.			Point Judith Atmosphere Stressed 75% Y.S.		
S. No.	Alloy and Temper	Filler Alloy	(1) Weld Condition	(2) Loading Method	Dash No.	Days to Fail	Exposure Date	Dash No.	Days to Fail	Exposure Date	Dash No.	Days to Fail	Exposure Date
320449	7039-T6	5183	AW	Bending - CD	1 + 2		1-18-65	5 + 6		1-20-65	9 + 10		3-6-65
				Bending - CD	3 + 4		1-18-65	7 + 8		1-20-65	11 + 12		3-6-65
				Direct Tension - CD	1		1-29-65	4		2-9-65	7		3-6-65
				Direct Tension - CD	2		1-29-65	5		2-9-65	8		3-6-65
				Direct Tension - CD	3		1-29-65	6		2-9-65	9		3-6-65
320449A	7039-T6	5183	PWA	Bending - CD	1 + 2		2-3-65	5 + 6		2-12-65	9 + 10		3-6-65
				Bending - CD	3 + 4		2-3-65	7 + 8		2-12-65	11 + 12		3-6-65
				Direct Tension - CD	1		1-29-65	4		2-9-65	7		3-6-65
				Direct Tension - CD	2		1-29-65	5		2-9-65	8		3-6-65
				Direct Tension - CD	3		1-29-65	6		2-9-65	9		3-6-65
320447	X7002-T6	X5180	AW	Bending - CD	1 + 2		1-18-65	5 + 6		1-20-65	9 + 10		3-6-65
				Bending - CD	3 + 4		1-18-65	7 + 8		2-9-65	11 + 12		3-6-65
				Direct Tension - CD	1		1-29-65	4		2-9-65	7		3-6-65
				Direct Tension - CD	2		1-29-65	5		2-9-65	8		3-6-65
				Direct Tension - CD	3		1-29-65	6		2-9-65	9		3-6-65
320447A	X7002-T6	X5180	PWA	Bending - CD	1 + 2		2-3-65	5 + 6		2-12-65	9 + 10		3-6-65
				Bending - CD	3 + 4		2-3-65	7 + 8		2-12-65	11 + 12		3-6-65
				Direct Tension - CD	1	65	1-29-65	4		2-9-65	7		3-6-65
				Direct Tension - CD	2	36	1-29-65	5		2-9-65	8		3-6-65
				Direct Tension - CD	3	76	1-29-65	6		2-9-65	9		3-6-65

Notes: (1) AW - As Welded; PWA - Post Weld Aged 8 hours at 225°F + 16 hours at 300°F.
(2) CD - Constant Deformation; CL - Constant Load.

TABLE XIV

Part A

STRESS CORROSION DATA ON 3/8" THICK Al-Zn-Mg ALLOY PLATE

S. No.	Alloy and Temper	Filler Alloy	Weld Condition (1)	Beam Assemblies - Constant Deformation: 3 1/2% NaCl - Alt. Imm. Stressed 75% Y.S. Dash No. (Pairs)	Days To Fail	Exposure Date	New Kensington Atmosphere Stressed 75% Y.S. Dash No. (Pairs)	Days To Fail	Exposure Date	Point Judith Atmosphere Stressed 75% Y.S. Dash No. (Pairs)	Days To Fail	Exposure Date
320445	X7106-T6351	X5180	AW	1 + 2 3 + 4		2-12-65 2-12-65	5 + 6 7 + 8		2-18-65 2-18-65	9 + 10 11 + 12		3-6-65 3-6-65
320445 A	X7106-T6351	X5180	PWA	1*+ 2 3*+ 4	35 42	2-12-65 2-12-65	5*+ 6* 7*+ 8	94 94	2-18-65 2-18-65	9 + 10 11 + 12		3-6-65 3-6-65
320445 M (2)	X7106-T6351	X5180	AW	1 + 2 3 + 4		2-26-65 2-26-65	5 + 6 7 + 8		3-2-65 3-2-65	9 + 10 11 + 12		
320445-MA (2)	X7106-T6351	X5180	PWA	1 + 2* 3*+4	39 32	2-26-65 2-26-65	5 + 6 7 + 8		3-2-65 3-2-65	9 + 10 11 + 12		
320452	X7139-T6351	X5180	AW	1 + 2 3 + 4		2-12-65 2-12-65	5 + 6 7 + 8		2-18-65 2-18-65	9 + 10 11 + 12		3-6-65 3-6-65
320452 A	X7139-T6351	X5180	PWA	1 + 2* 3 + 4	37 110	2-12-65 2-12-65	5 + 6 7 + 8*	88	2-18-65 2-18-65	9*+ 10 11*+ 12	97 97	3-6-65 3-6-65
320450	7039-T651	5183	AW	1 + 2 3 + 4		2-12-65 2-12-65	5 + 6 7 + 8		2-18-65 2-18-65	9 + 10 11 + 12		3-6-65 3-6-65
320450 A			PWA	1 + 2 3 + 4		2-12-65 2-12-65	5 + 6 7 + 8		2-18-65 2-18-65	9 + 10 11 + 12		3-6-65 3-6-65
320448	X7002-T651	X5180	AW	1 + 2 3 + 4		2-12-65 2-12-65	5 + 6 7 + 8		2-18-65 2-18-65	9 + 10 11 + 12		3-6-65 3-6-65

Notes: (1) AW - As Welded; PWA - Post Weld Aged 8 hours at 225°F + 16 hours at 300°F.
(2) DCRP-MIG welded; others DCSP-TIG welded.
* Indicates the specimen that failed in the beam assembly.

Part B

WELD TENSILE PROPERTIES AND STRESS CORROSION DATA ON 1" THICK X7106-T6351 PLATE DCRP-MIG WELDED WITH X5180 IN SIX PASSES (1)

S. No.	Weld Tensile Properties: T.S. ksi	Y.S. ksi	El. (10") %	3 1/2% NaCl - Alternate Immersion Stressed 75% Y.S.: Dash No. (Pairs)	Days to Fail	Exposure Date	New Kensington Atmosphere Stressed 75% Y.S.: Dash No. (Pairs)	Days to Fail	Exposure Date	Point Judith Atmosphere Stressed 75% Y.S.: Dash No. (Pairs)	Days to Fail	Exposure Date
320446 AW	52.0	38.3 (3)	3.0	1 & 2 (4)		4-23-65	5 & 6		4-30-65	9 & 10		5-29-65
				3 & 4		4-23-65	7 & 8		4-30-65	11 & 12		5-29-65
320446-A PWA (2)	54.9	49.3	2.2	A1* & A2 (5)	21	4-23-65	A5* & A6*	35	4-30-65	A9 & A10		5-29-65
				A3 & A4		4-23-65	A7* & A8*	33	4-30-65	A11 & A12		5-29-65

Notes: (1) Welded in six passes - 1, 3, 5 on front side and 2, 4, 6 on back side in opposite direction.
(2) Post-weld aged 8 hours at 225°F + 16 hours at 300°F.
(3) Based on only one full section specimen as yield strength on duplicate specimen was not able to be obtained due to a malfunction of the strain recorder.
(4) Stressed by Engineering Design Division using dial gauge for deflection based upon strain gauge requirement.
(5) Stressed by Engineering Design Division to deflection measurements obtained by simple beam formula.
* Indicates the specimen that failed in the beam assembly.

TABLE XV

STRESS CORROSION DATA ON 3/8" THICK X7106 ALLOY PLATE AND FORGING COMBINATIONS
DCSP-TIG WELDED WITH X5180 FILLER

			Beam Assemblies - Constant Deformation								
			3 1/2% NaCl - Alt. Imm. Stressed 75%Y.S.			New Kensington Atmosphere Stressed 75%Y.S.			Point Judith Atmosphere Stressed 75%Y.S.		
S. No.	Alloy and Temper	(1) Weld Condition	Dash No. (Pairs)	Days To Fail	Exposure Date	Dash No. (Pairs)	Days To Fail	Exposure Date	Dash No. (Pairs)	Days To Fail	Exposure Date
320426 S	X7106-T6352 Forging (Short Transverse)	AW	1 + 2 3 + 4		2-12-65 2-12-65	5 + 6 7 + 8		2-18-65 2-18-65	9 + 10 11 + 12		3-6-65 3-6-65
320426 SA	X7106-T6352 Forging (Short Transverse)	PWA	1 + 2 3 + 4*	42	2-12-65 2-12-65	5 + 6 7 + 8	108	2-18-65 2-18-65	9 + 10 11 + 12		3-6-65 3-6-65
320426 S 320445	X7106-T6352 Forging(ST) X7106-T6351 Plate (LT)	AW	1 + 2 3 + 4		2-12-65 2-12-65	5 + 6 7 + 8		2-18-65 2-18-65	9 + 10 11 + 12		3-6-65 3-6-65
320426 SA 320445 A	X7106-T6352 Forging(ST) X7106-T6351 Plate (LT)	PWA	1*+ 2 3*+ 4	35 42	2-12-65 2-12-65	5 + 6 7 + 8		2-18-65 2-18-65	9 + 10 11 + 12		3-6-65 3-6-65
320426 S 320445	Same as Above Plus Painted (2)	AW	13 + 14 15 + 16		3-24-65 3-24-65	17 + 18 19 + 20		3-25-65 3-25-65	21 + 22 23 + 24		5-29-65 5-29-65
320426 SA 320445 A	Same as Above Plus Painted (2)	PWA	A13 + A14 A15 + A16		3-24-65 3-24-65	A17 + A18 A19 + A20		3-25-65 3-25-65	A21 + A22 A23 + A24		5-29-65 5-29-65
320426 L 320445	X7106-T6352 Forging(LT) X7106-T6351 Plate (ST)	AW	1 + 2 3 + 4		2-12-65 2-12-65	5 + 6 7 + 8		2-18-65 2-18-65	9 + 10 11 + 12		3-6-65 3-6-65
320426 LA 320445 A	X7106-T6352 Forging(LT) X7106-T6351 Plate (ST)	PWA	1 + 2* 3*+ 4	25 19	2-17-65 2-17-65	5 + 6 7 + 8	88 75	2-18-65 2-18-65	9 + 10 11 + 12	36 97	3-6-65 3-6-65
320426 L 320445	Same as Above Plus Painted (2)	AW	13 + 14 15 + 16		3-24-65 3-24-65	17 + 18 19 + 20		3-25-65 3-25-65	20 + 21 22 + 23		5-29-65 5-29-65
320426 LA 320445 A	Same as Above Plus Painted (2)	PWA	A13 + A14 A15 + A16	77 70	3-24-65 3-24-65	A17 + A18 A19 + A20		3-25-65 3-25-65	A20 + A21 A22 + A23		5-29-65 5-29-65

Notes: (1) AW - As Welded; (2) PWA - Post Weld Aged 8 hours at 225°F + 16 hours at 300°F
(2) Paint System - Alodine 1200 plus Strontium Chloride Epoxy Primer (1 mil) plus Epoxy Polyamide (2 mil).
* Indicates the specimen that failed in the beam assembly.

TABLE XVI

STRESS CORROSION DATA ON WELDED "H" PLATE SPECIMENS OF 1/8", 3/8" AND 1.0" THICK Al-Zn-Mg ALLOYS

S. No.	Alloy and Temper	Filler Alloy	Welding Method	Weld Condition (1)	3 1/2% NaCl - Alternate Immersion: Dash No.	Avg. Stress ksi (2)	Days to Failure	Exposure Date	New Kensington Atmosphere: Dash No.	Avg. Stress ksi (2)	Days to Failure	Exposure Date	Point Judith Atmosphere: Dash No.	Avg. Stress ksi (2)	Days to Failure	Exposure Date
					1/8" Thick "H" Plates											
320444 & A	X7106-T6	X5180	DCSP-TIG	AW	1	14.4		4-13-65	3	14.8		5-3-65	5	15.5		8- -65
					2	14.9		4-13-65	4	16.0		5-3-65	6	13.5		8- -65
				PWA	A1	13.4		5-14-65	A3	10.3		5-3-65	A5	17.2		8- -65
					A2	15.4		5-14-65	A4	9.1		5-3-65	A6	13.8		8- -65
320451 & A	X7139-T6	X5180	DCSP-TIG	AW	49	15.9		4-13-65	51	16.1		5-3-65	53	16.4		8- -65
					50	16.5		4-13-65	52	16.2		5-3-65	54	15.3		8- -65
					A49	15.7		5-14-65	A51	15.4		5-3-65	A53	12.2		8- -65
					A50	14.1		5-14-65	A52	16.8	88	5-3-65	P2	6.8		8- -65
320449 & A	7039-T6	5183	DCSP-TIG	AW	37	16.3		4-13-65	39	16.9		5-3-65	41	16.6		8- -65
					38	16.2		4-13-65	40	17.3		5-3-65	42	16.2		8- -65
				PWA	A37	14.6		5-14-65	A39	14.8		5-3-65	A41	15.8		8- -65
					A38	14.7		5-14-65	A40	14.8		5-3-65	A42	13.9		8- -65
320447 & A	X7002-T6	X5180	DCSP-TIG	AW	25	10.2		4-13-65	27	16.6		5-3-65	29	17.8		8- -65
					26	15.0		4-13-65	28	15.9		5-3-65	30	15.7		8- -65
				PWA	A25	15.8		5-14-65	A27	13.6		5-3-65	A29	15.4		8- -65
					A26	14.0		5-14-65	A28	14.5		5-3-65	A30	13.1		8- -65
					3/8" Thick "H" Plates											
320445 & A	X7106-T6351	X5180	DCSP-TIG	AW	9	17.6		6-9-65	12	21.1		6-22-65	11X	20.2		8- -65
					8X	20.7		4-29-65	A12	18.6		6-22-65	---	----		
				PWA	A7	17.0		6-9-65	A9	15.7			A11	18.2		6- -65
					A8X	16.6		5-19-65	A10X	16.0		5-20-65	---	----		
320445M & MA	X7106-T6351	X5180	DCRP-MIG	AW	13	19.8		3-29-65	15	19.8		5-3-65	17	23.1		8- -65
					14	13.0		3-29-65	16	18.6		5-3-65	18	25.4		8- -65
				PWA	A13	17.8		4-2-65	A15	16.5		5-3-65	A17	19.4		8- -65
					A14	17.8		4-2-65	A16	20.1		5-3-65	A18	19.3		8- -65
320452 & A	X7139-T6351	X5180	DCWP-TIG	AW	55	21.2		3-29-65	57	23.7		5-3-65	59	20.9		8- -65
					56	21.0		3-29-65	58	19.0		5-3-65	60	17.0		8- -65
				PWA	A55	17.7		4-2-65	A57	18.7		5-3-65	A59	14.9		8- -65
					A56	16.8		4-2-65	A58	14.9		5-3-65	A60	18.2		8- -65
320450 & A	7039-T651	5183	DCSP-TIG	AW	43	15.7		3-29-65	45	11.7		5-3-65	47	13.8		8- -65
					44	11.0		3-29-65	46	12.8		5-3-65	48	16.4		8- -65
				PWA	A43	15.7		4-29-65	A45	13.2		5-3-65	A47	14.3		8- -65
					A44	12.9		4-29-65	A46	15.3		5-3-65	A48	15.0		8- -65
320448	X7002-T651	X5180		AW	31	22.7		4-29-65	33	20.5		5-3-65	35	22.4		8- -65
					32	22.8		4-29-65	34	20.5		5-3-65	36	19.9		8- -65
320426S & SA	X7106-T6352 Forging Short Transverse	X5180	DCSP-TIG	AW	61	19.8		6-4-65	63	23.8		5-20-65	65	20.5		6-6-65
					A61	21.6		6-22-65	A63	20.7		5-20-65	A65	23.6		6-6-65
					1.0" Thick "H" Plates											
320446 & A	X7106-T6351	X5180	DCRP-MIG	AW	19	25.3		4-6-65	21	29.6		5-3-65	23	22.8		8- -65
					20	27.2		4-6-65	22	26.0		5-3-65	24	26.5		8- -65
				PWA	A19	35.5*		5-19-65	A21	28.6*		5-3-65	A23	37.3*		6-6-65
					A20	40.5*		5-19-65	A22	38.7*		5-3-65	A24	37.1*		6-6-65

Notes: (1) AW - as welded; PWA - post weld aged 8 hours at 225°F + 16 hours at 300°F.
(2) Combination of residual welding stresses plus stress obtained by removing a portion of the center strut to make a common two-inch wide test region.
* Residual stresses obtained on specimens prepared for tensile properties. Stresses in actual specimens to be determined at end of test.

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APPENDIX B

(2)

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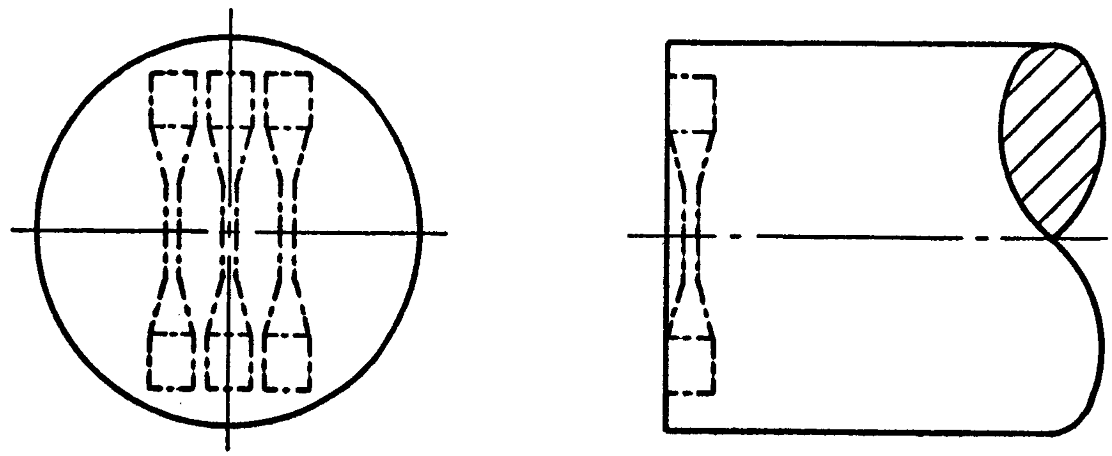
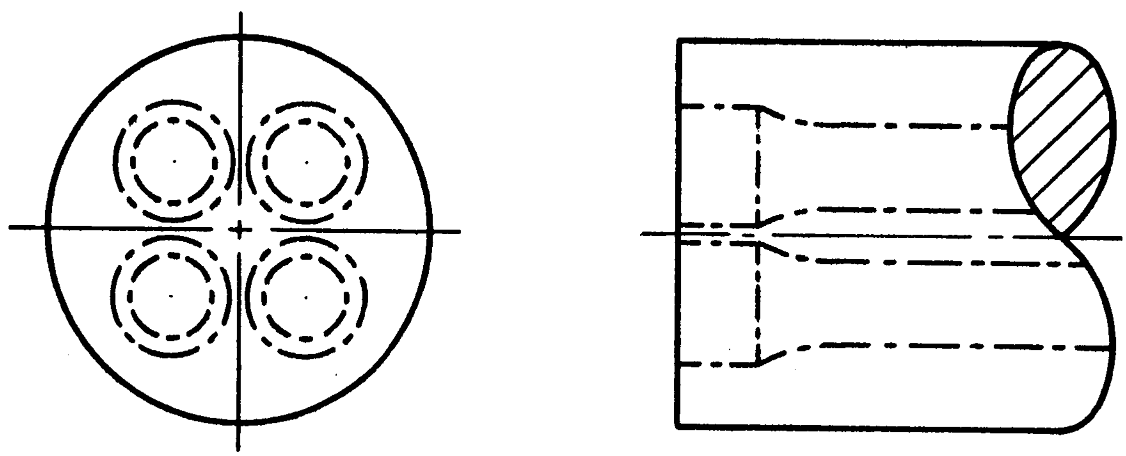
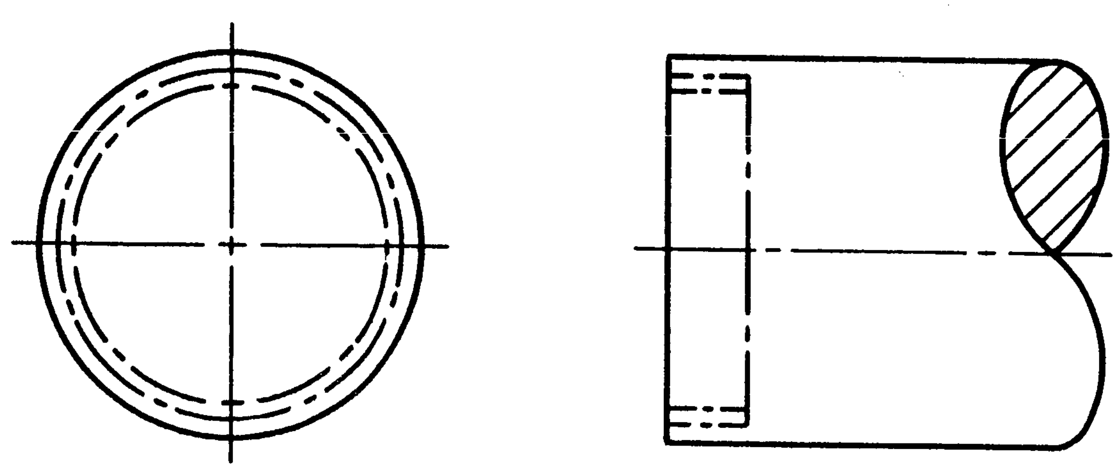
51. Theoretical Evaluation During Cracking of Stress Corrosion Specimen in Bending Fixture.



(a) 0.125-in. diam x 2-in. long tensile test specimens



(b) 0.500-in. diam tapered seat tensile test specimens



(c) 2.25-in. O.D. x 0.125-in. wall interference ring

FIG. 1 – LOCATION OF TEST SPECIMENS IN 2 1/2-IN. DIAM ROLLED ROD

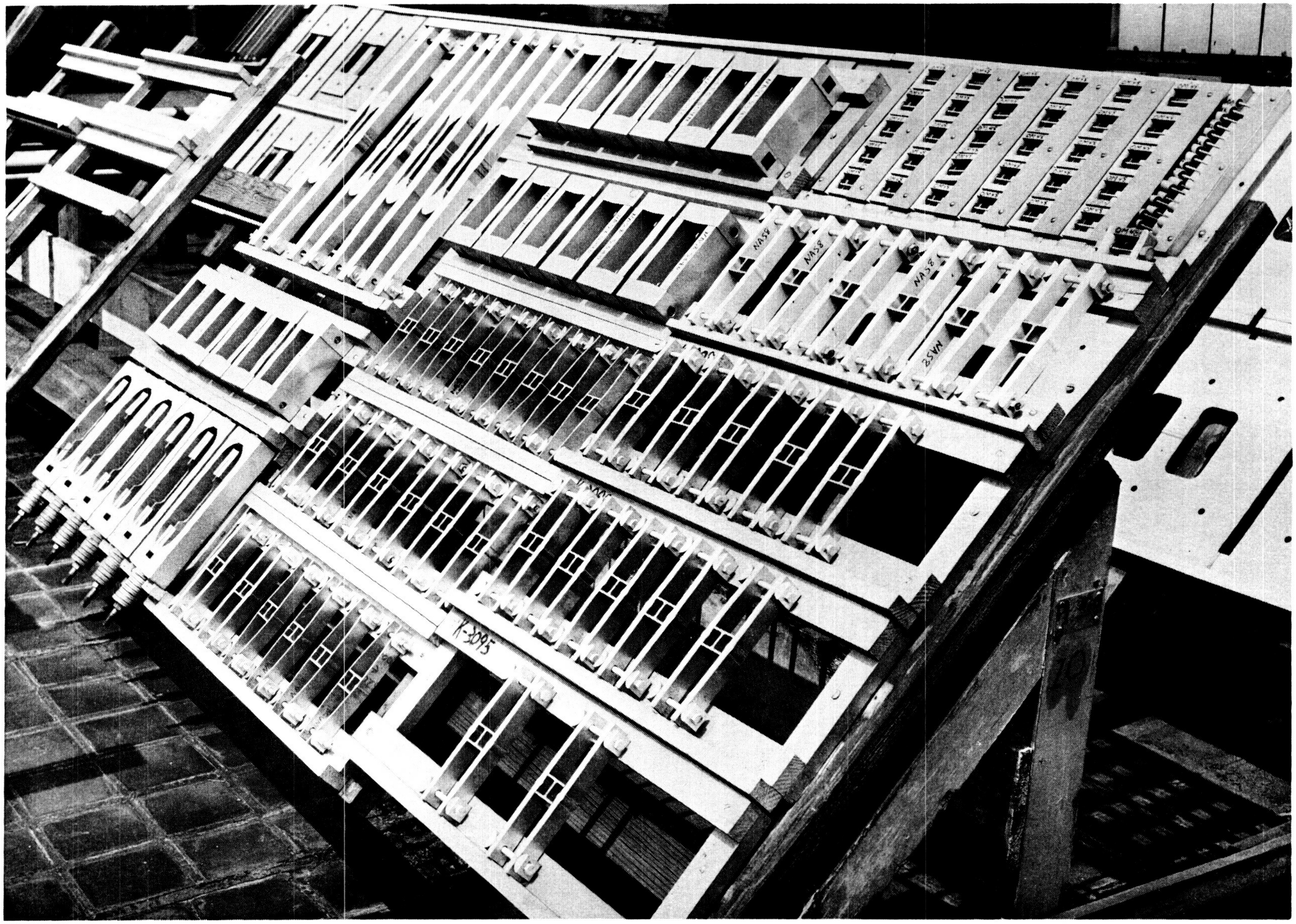
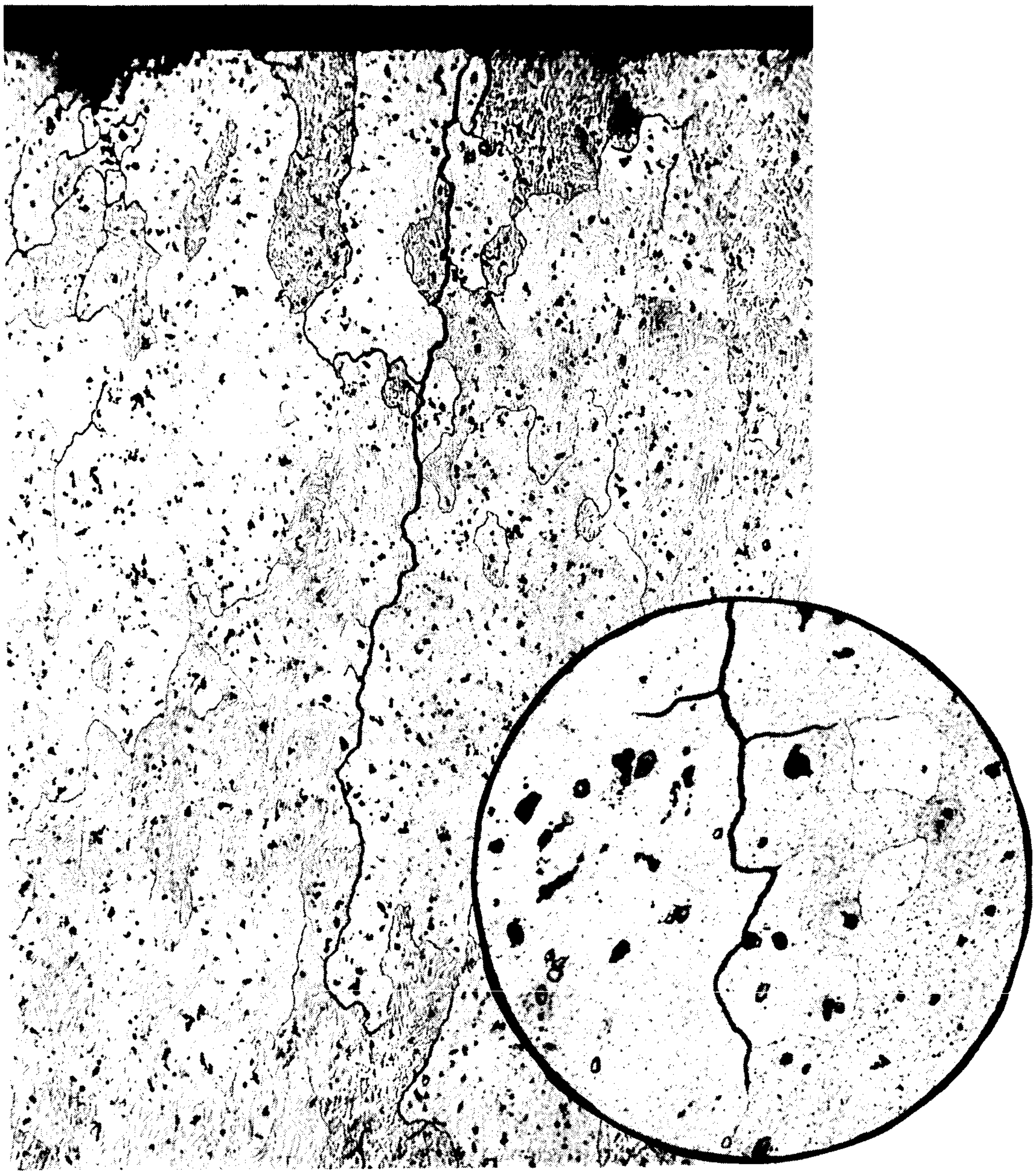


Figure 2 - Portion of the New Kensington Atmosphere facility

Figure 3

Shows the appearance of a typical stress-corrosion crack adjacent to the fracture in one of the 2024-T351 specimens. The definite intergranular nature of the leading tip of the crack is shown in greater detail in the insert.



S-302210-T10

Mag. 100X (500X)

Etch - Keller's

Figure - 3

140496AJ

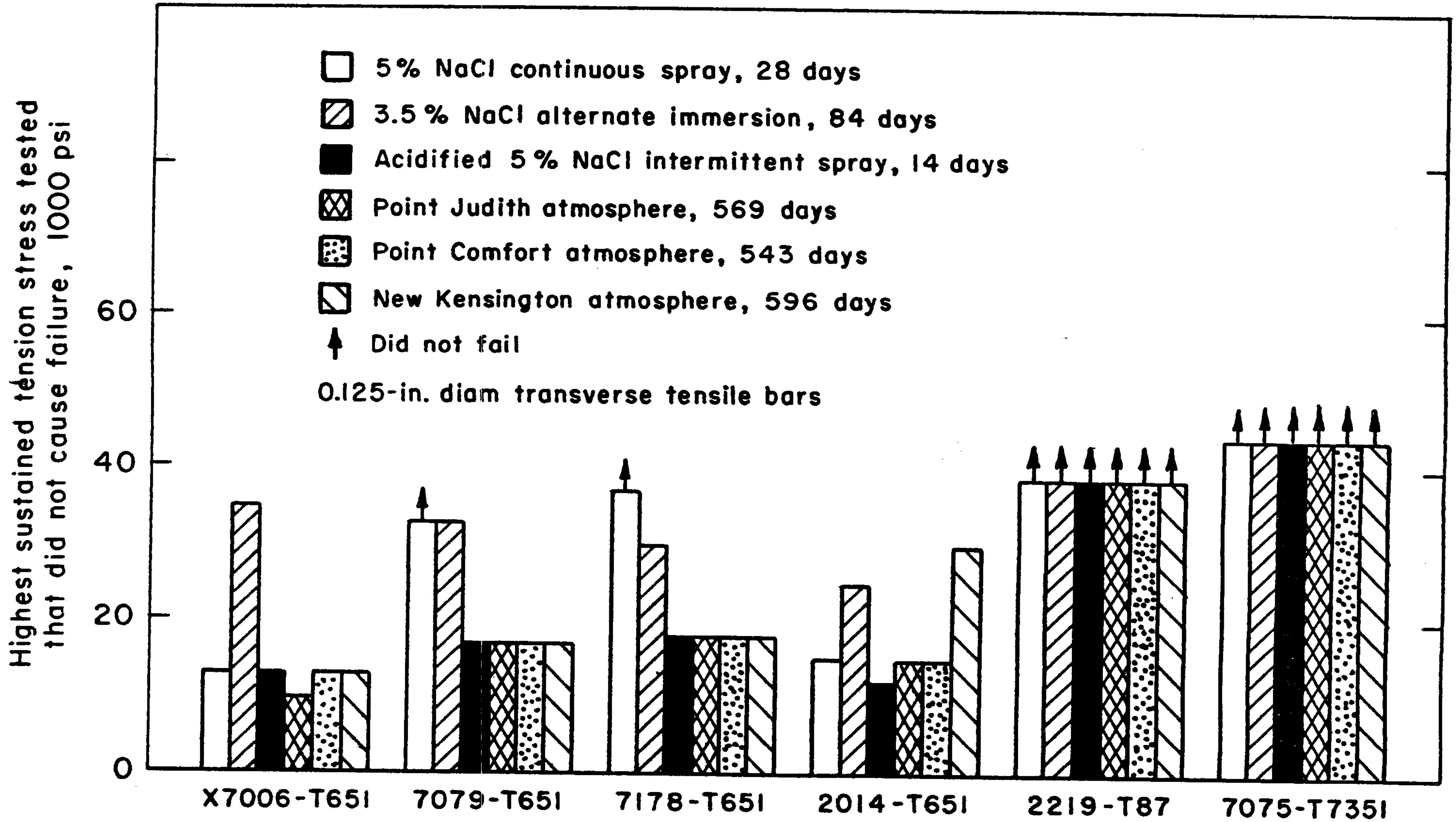
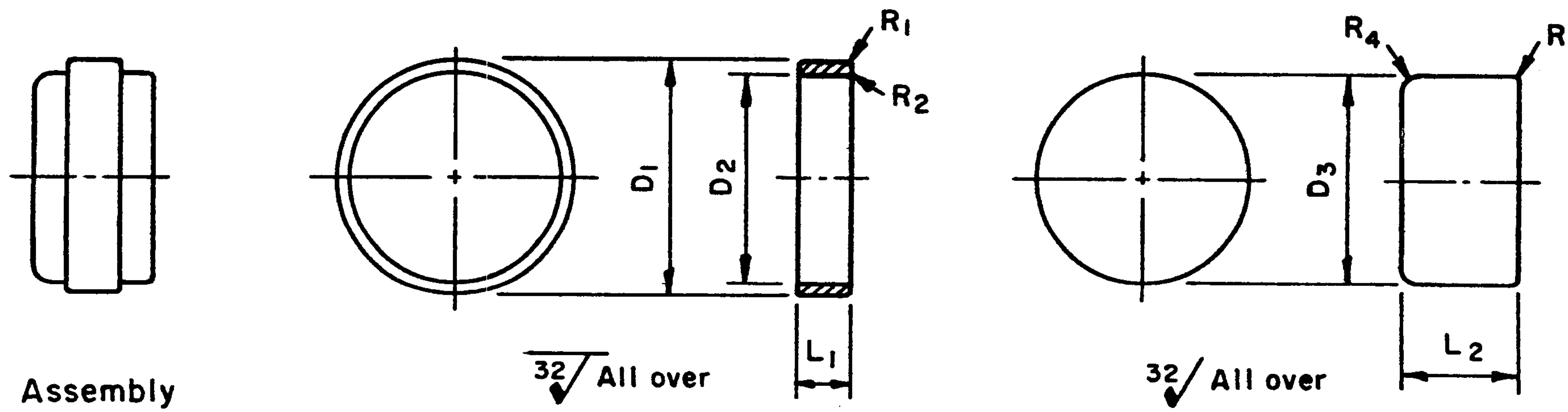


FIG. 4 — RELATIVE RESISTANCE TO STRESS-CORROSION CRACKING OF THE SIX ITEMS OF 2 1/2-IN. DIAMETER ALUMINUM ALLOY ROLLED ROD



O-Ring S.C.C. specimen

R_1 = 1/64-in. if exposed bare
1/16-in. if to be painted
R_2 = 1/64-in.
L_1 = 0.500-in. ± 1/64-in.
D_1 = 2.250-in. ±0.0020-in.
D_2 = 2.000-in. ±0.0010-in.

Stressing plug

R_3 = 1/64-in.
R_4 = 1/8-in.
L_2 = 1.125-in. ± 1/32-in.
D_3 = Individual ring inside diameter plus calculated interference ± 0.0005-in.

FIG. 6 — INTERFERENCE RING STRESS-CORROSION SPECIMEN

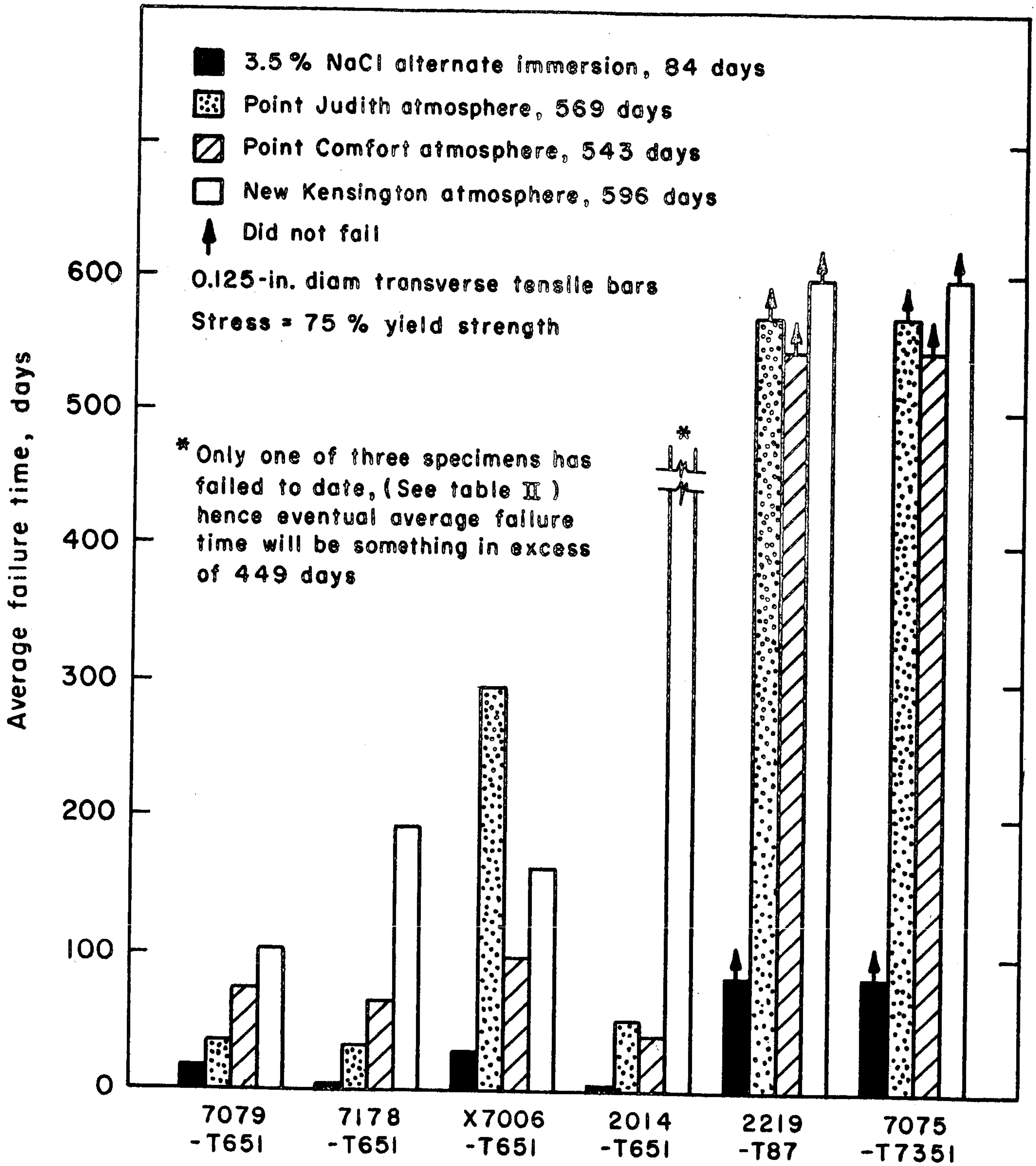


FIG. 5 – COMPARATIVE FAILURE TIMES OF SEVERAL ALUMINUM ALLOYS OF 2½-IN. DIAMETER ROLLED ROD EXPOSED TO VARIOUS ENVIRONMENTS

Figure 7

As-machined specimens exposed six months to 3.5% NaCl alternate immersion. Specimens were photographed after chemical cleaning and mechanical testing. Uniform general corrosion occurred on the gauge length area, varying in intensity with alloy composition. The grip ends show noticeably less attack because this area had been protected during exposure by a strippable plastic. This latter procedure was employed on specimens of all systems. The per cent reductions in mechanical properties due to corrosion of these specimens are listed below:

Alloy	Per Cent Reduction T.S.	Per Cent Reduction El.
2014-T651	1	43
7079-T651	0	12
2024-T351	4	37
7178-T651	2	43
2219-T87	5	35
7075-T7351	0	21

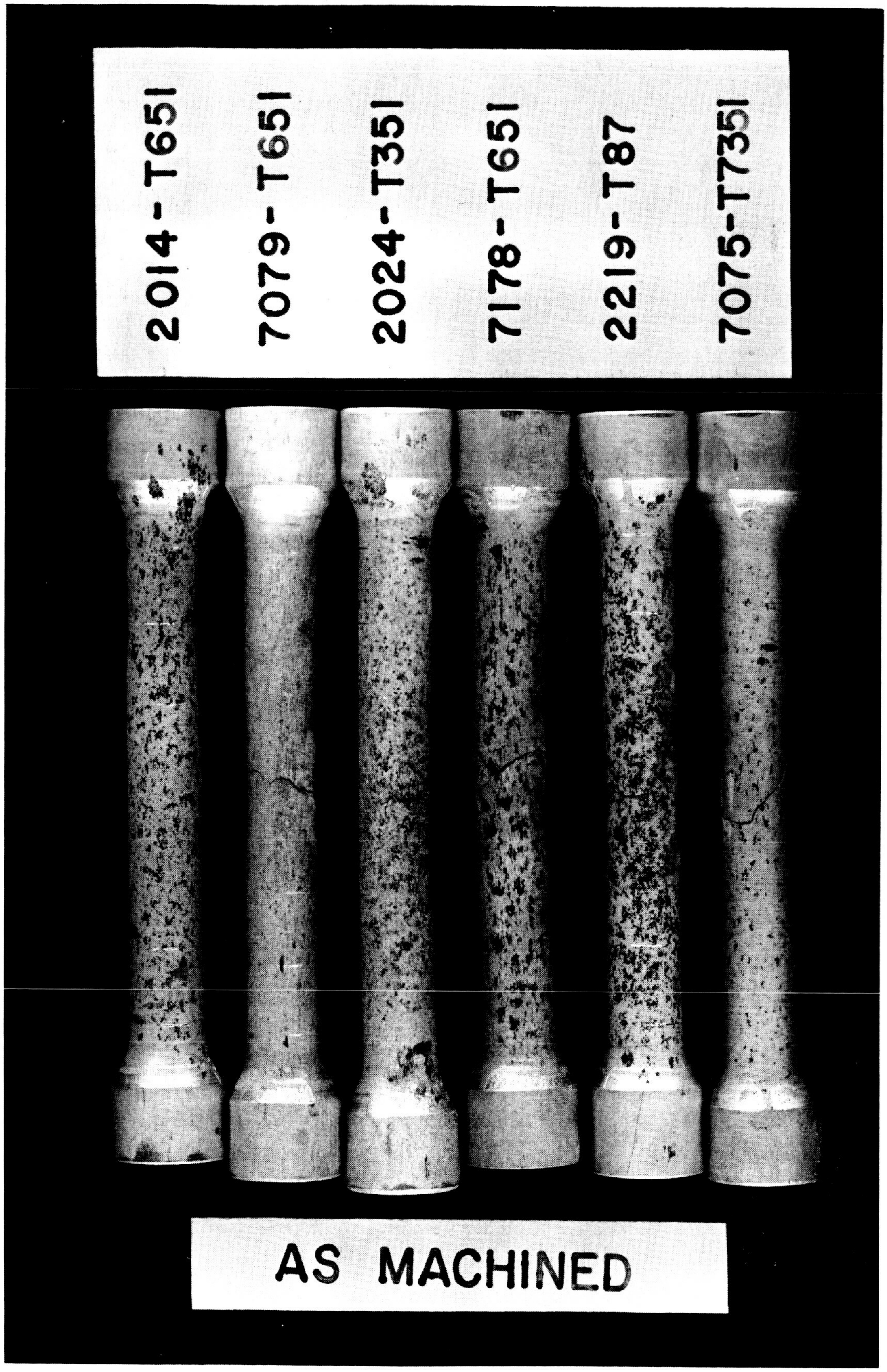
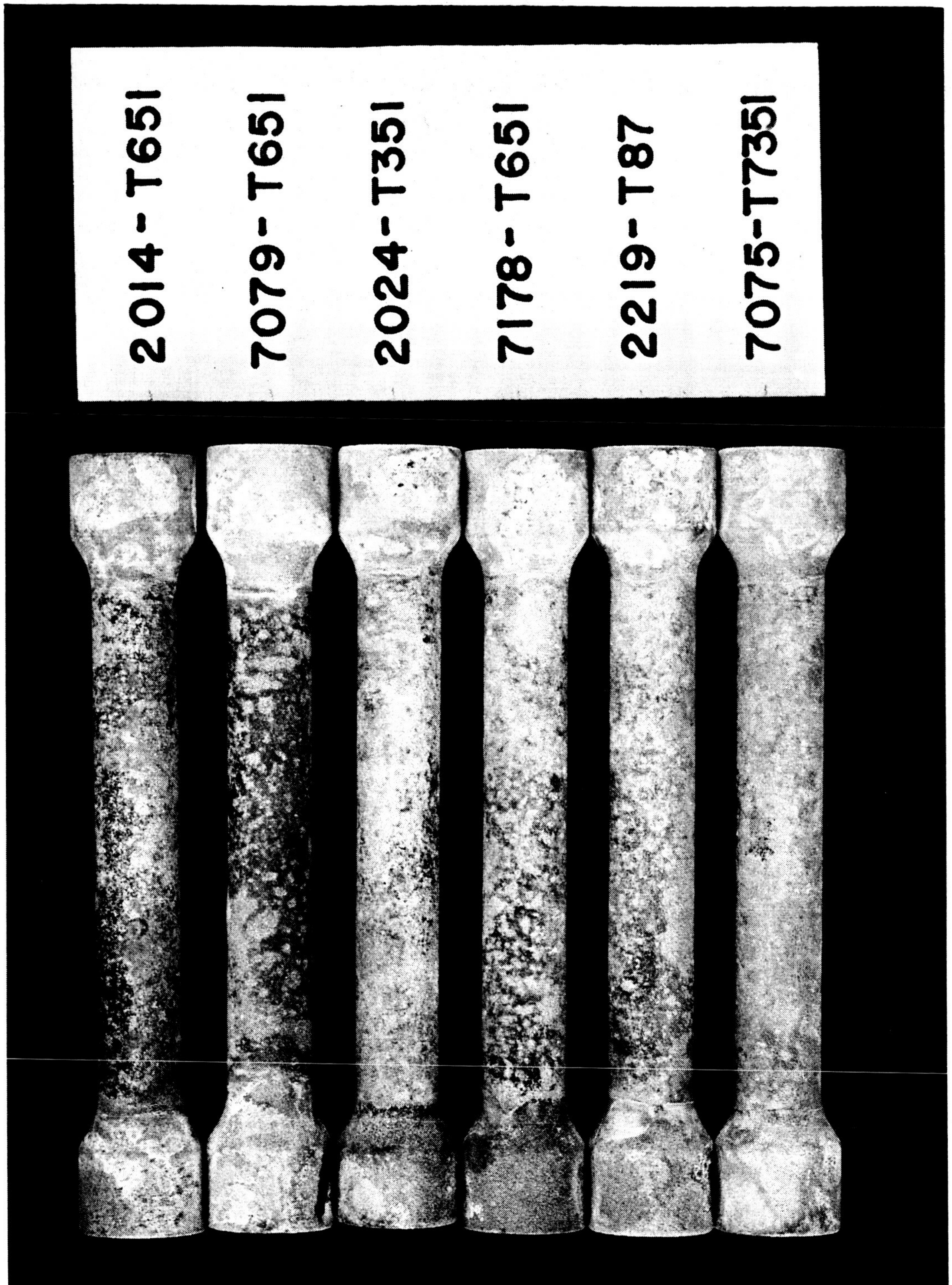

2014 - T651
7079 - T651
2024 - T351
7178 - T651
2219 - T87
7075-T7351
AS MACHINED

Figure - 7

Figure 8

Metallized specimens exposed one year to 3.5% NaCl alternate immersion. Specimens were chemically cleaned. Moderate general surface attack occurred but did not penetrate the metallized coating which was still intact and adherent. The per cent reductions in mechanical properties due to corrosion of these specimens are listed below:

Alloy	Per Cent Reduction T.S.	Per Cent Reduction El.
2014-T651	0	7
7079-T651	0	14
2024-T351	1	54
7178-T651	0	23
2219-T87	0	6
7075-T7351	2	5



SYSTEM 3 (7072 Metallized)

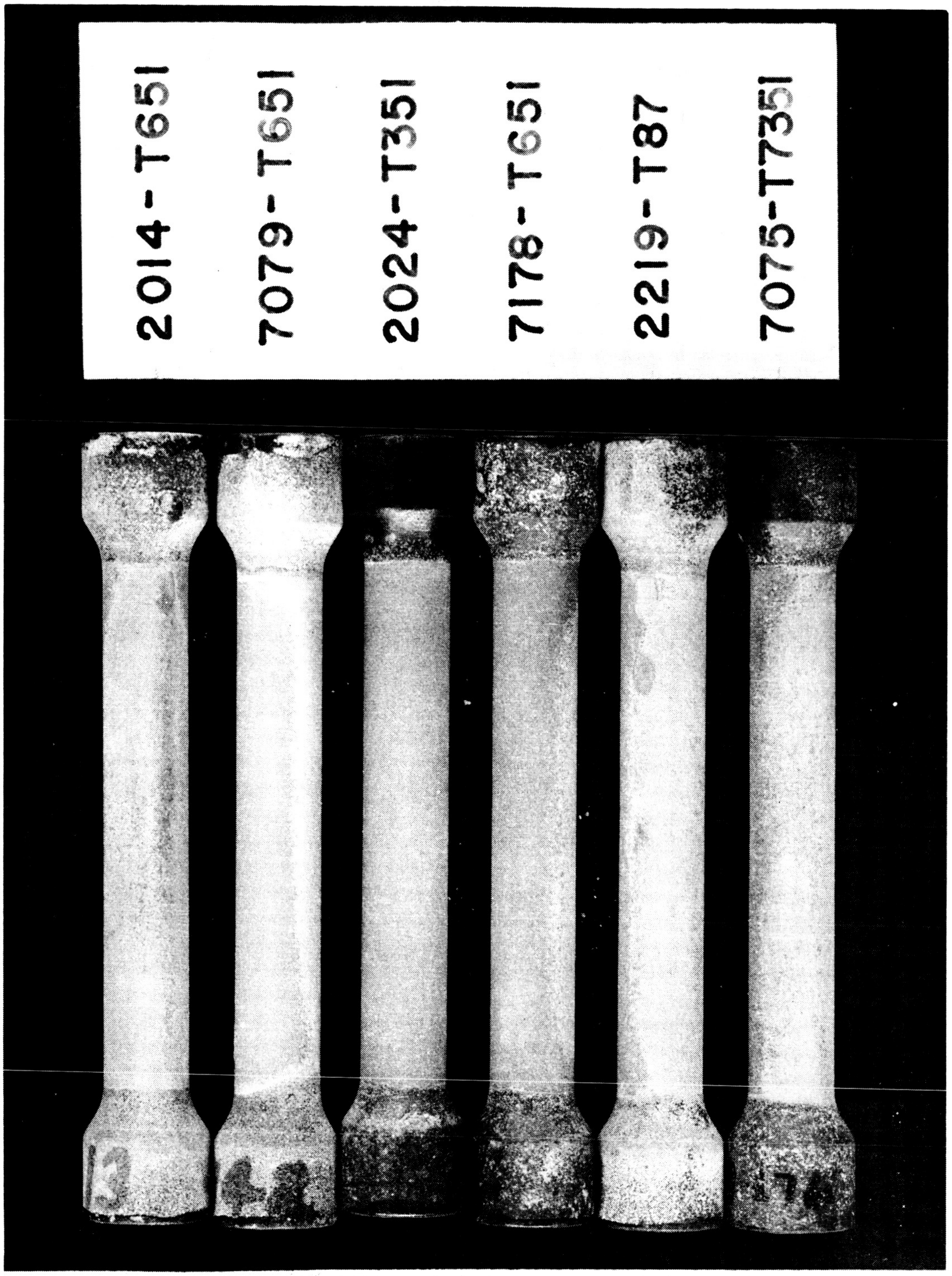
Figure - 8

PCL184CJ

Figure 9

Zinc rich paint coated specimens exposed one year to 3.5% NaCl alternate immersion. Specimens cleaned in tap water. The paint system was intact with no signs of corrosion of the aluminum. However, as with System 7 the coating itself was deteriorated as evidenced by the different appearance of the gauge length and grip ends. The per cent reductions in mechanical properties due to corrosion of these specimens are listed below:

Alloy	Per Cent Reduction T.S.	Per Cent Reduction El.
2014-T651	0	0
7079-T651	0	1
2024-T351	0	25
7178-T651	0	5
2219-T87	0	3
7075-T7351	0	2



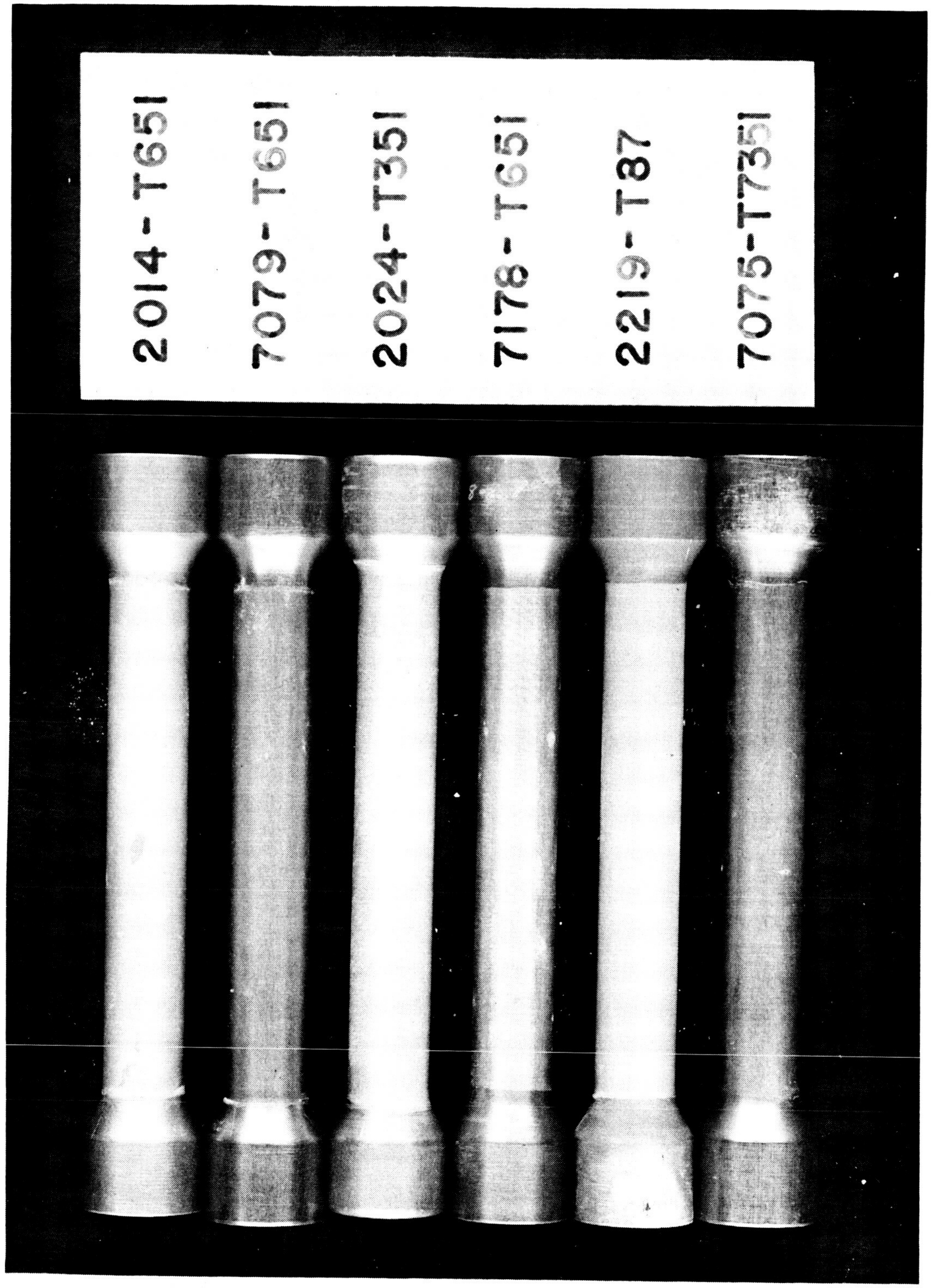
SYSTEM 13 (Epoxy Polyamide + Zinc Pigment)

Figure - 9

Figure 10

Alumilite 205 coated specimens exposed one year to 3.5% NaCl alternate immersion. Specimens cleaned in tap water. No obvious sites of attack of the aluminum were noted and the coating appeared in good condition, though some deterioration did occur as evidenced by color variation between gauge length and grip ends. The per cent reductions in mechanical properties due to corrosion of these specimens are listed below:

Alloy	Per Cent Reduction T.S.	Per Cent Reduction El.
2014-T651	0	0
7079-T651	0	4
2024-T351	0	5
7178-T651	0	4
2219-T87	0	0
7075-T7351	2	2



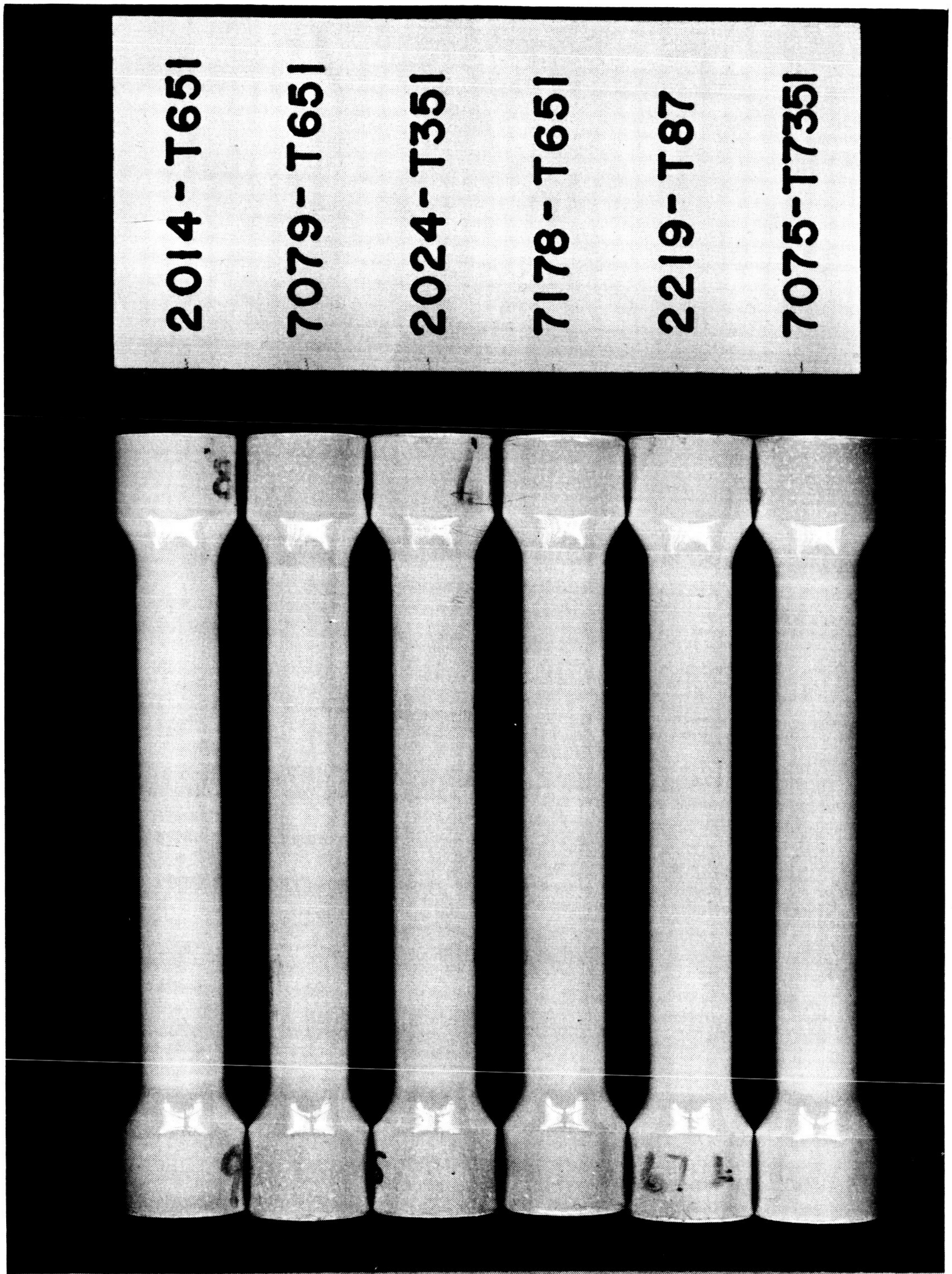
SYSTEM 5 (Alumilite 205)

Figure -10

Figure 11

Epoxy polyamide painted specimens exposed one year to 3.5% NaCl alternate immersion. Specimens cleaned in tap water. No obvious signs of coating breakdown or attack of aluminum; variation between grip ends and gauge length was primarily a difference in paint luster. Photograph is also representative of Systems 9, 10, 11, 12, 14 and 15. The per cent reductions in mechanical properties due to corrosion of these specimens are listed below:

Alloy	Per Cent Reduction T.S.	Per Cent Reduction El.
2014-T651	0	0
7079-T651	0	4
2024-T351	0	8
7178-T651	0	2
2219-T87	0	0
7075-T7351	1	1



SYSTEM 8 (Alodine 1200 + Epoxy Polyamide)

Figure -11

PCL185CJ

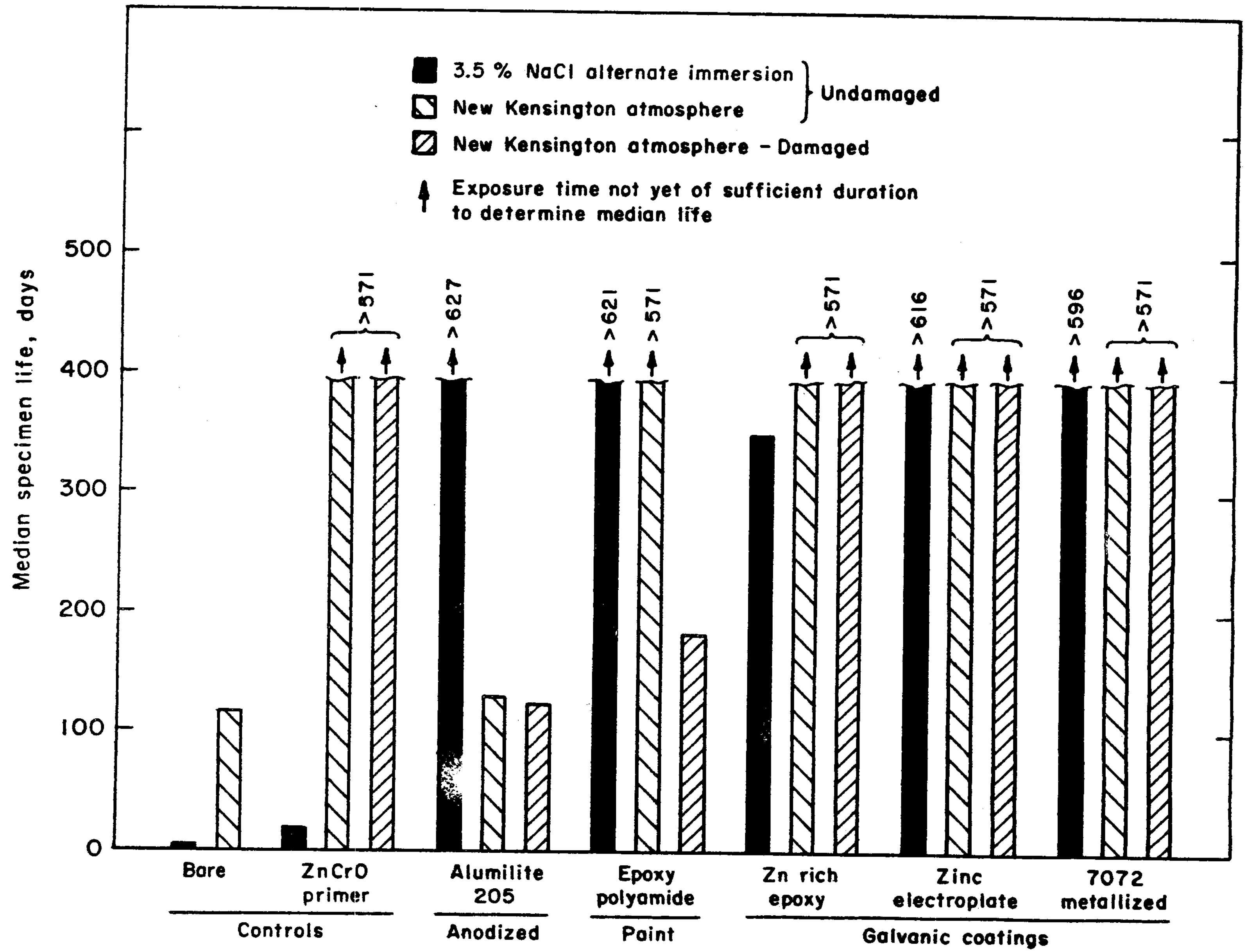


FIG. 12 – COMPARISON OF THE DEGREE OF PROTECTION AGAINST STRESS-CORROSION CRACKING THAT WAS AFFORDED TO THE 2014-T651 SPECIMENS BY VARIOUS PROTECTIVE SYSTEMS

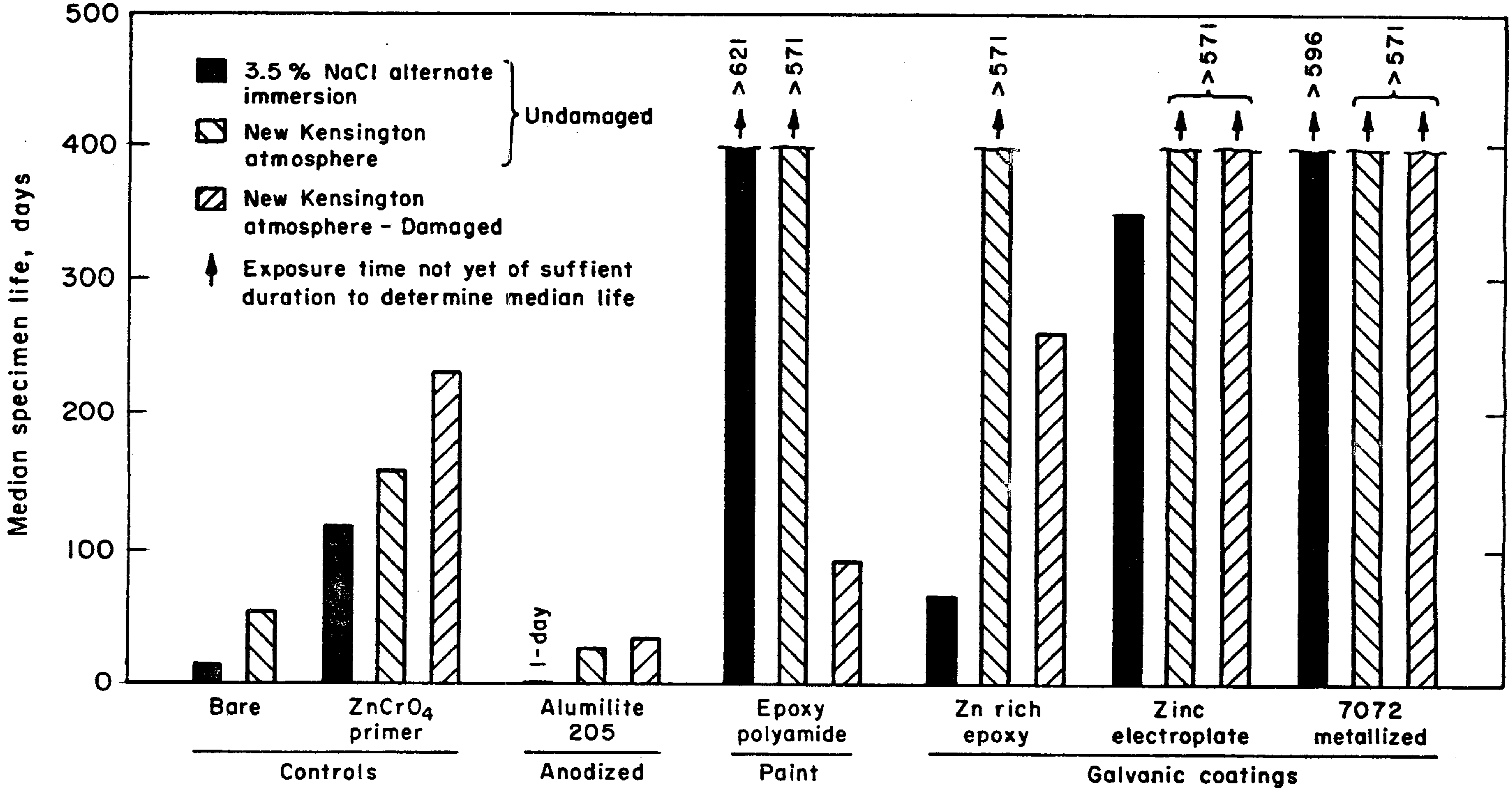


FIG. 13 - COMPARISON OF THE DEGREE OF PROTECTION AGAINST STRESS-CORROSION CRACKING THAT WAS AFFORDED TO THE 7079-T651 SPECIMENS BY VARIOUS PROTECTIVE SYSTEMS

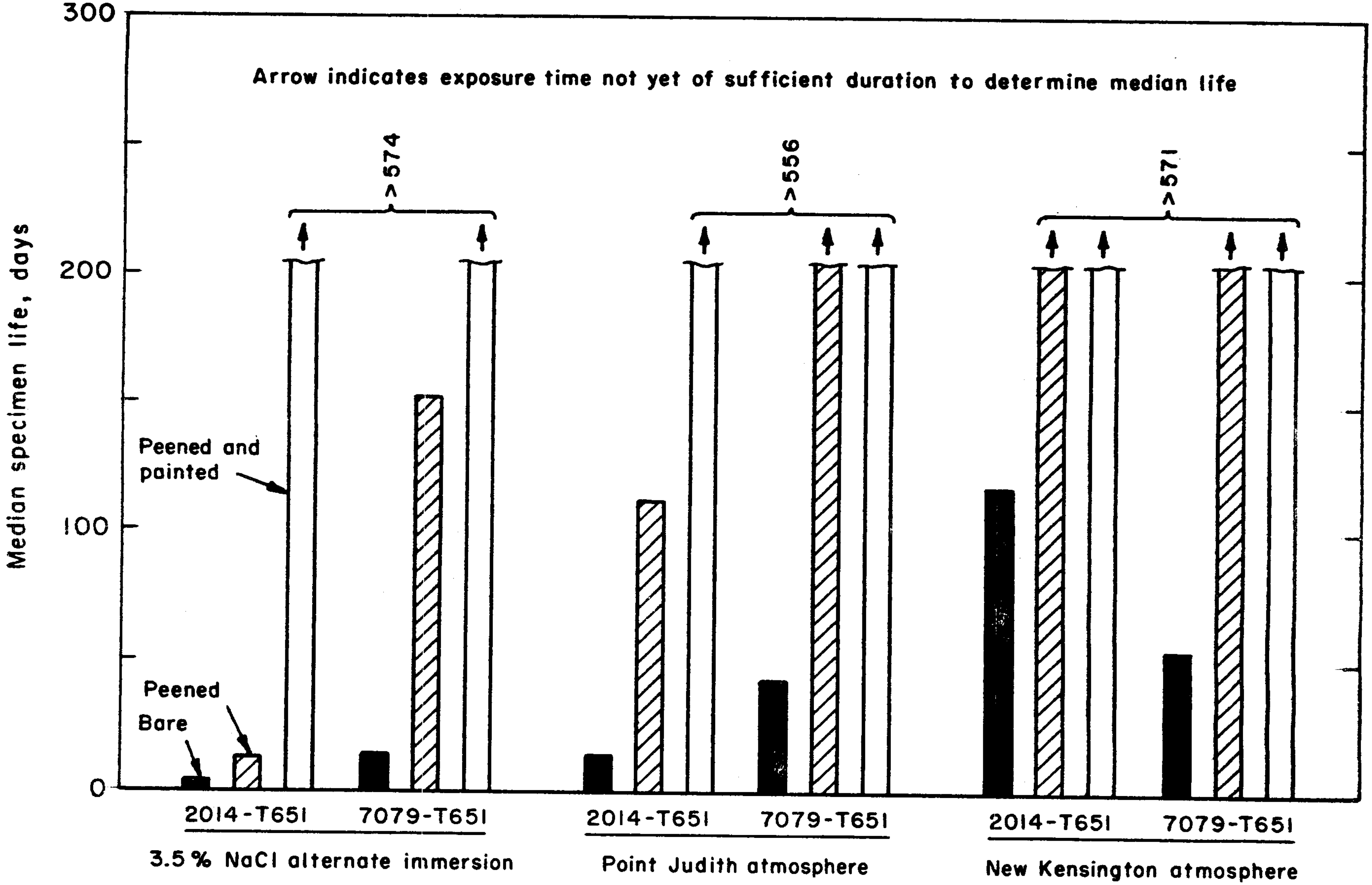


FIG. 14 – COMPARISON OF THE EFFECT OF ALLOY AND ENVIRONMENT ON THE PROTECTION AGAINST STRESS-CORROSION CRACKING AFFORDED BY PEENING AND BY PEENING PLUS PAINTING

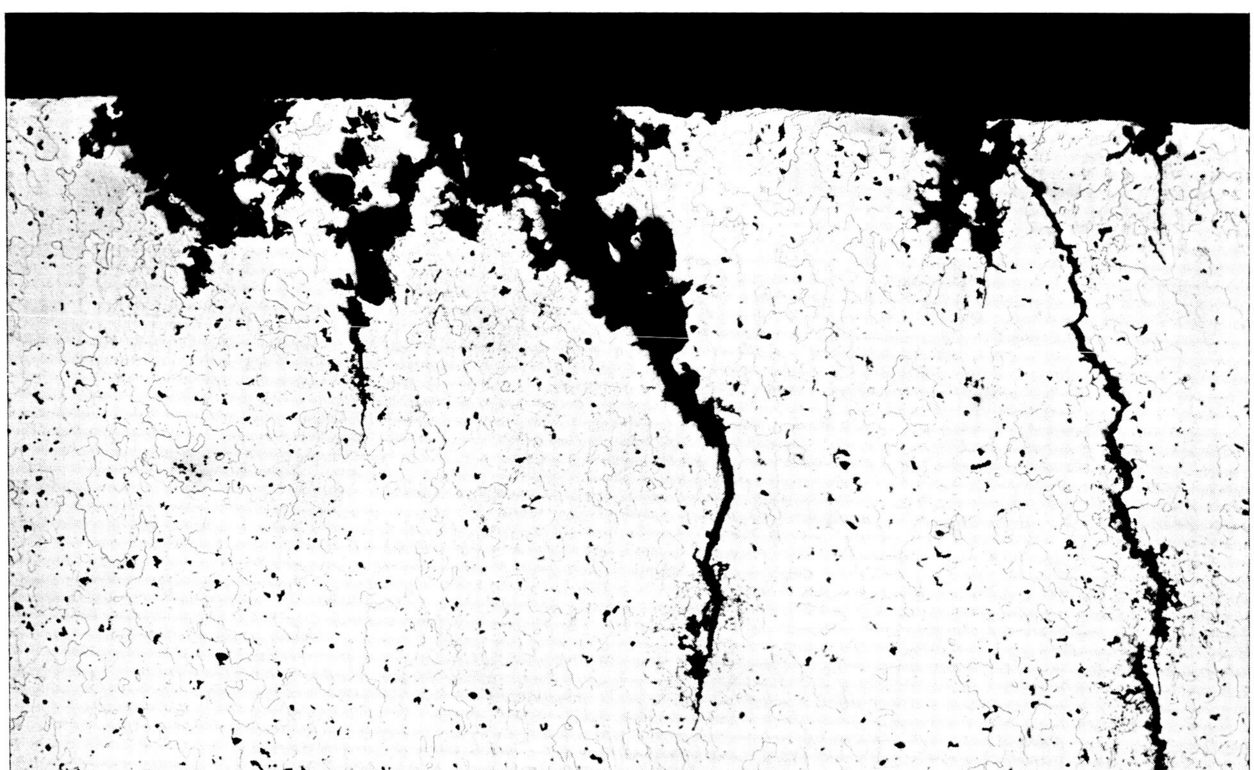
Figure 15

Shows the condition of one of the 7075-T7351 ring specimens exposed 553 days to 3.5% NaCl alternate immersion after cleaning in concentrated nitric acid. In addition to the principal fracture in the foreground, several other cracks can be seen extending part way through the specimen. This condition is representative of all the 7075-T7351 rings exposed to alternate immersion.

Figure 16

Section from the above 7075-T7351 ring exhibiting a large amount of transgranular cracking. The photo also illustrates the pitting plus slight intergranular (P + SI) attack on the surface and the manner in which all cracks (both intergranular and transgranular) initiated from this attack.

Figure - 15



144277AJ

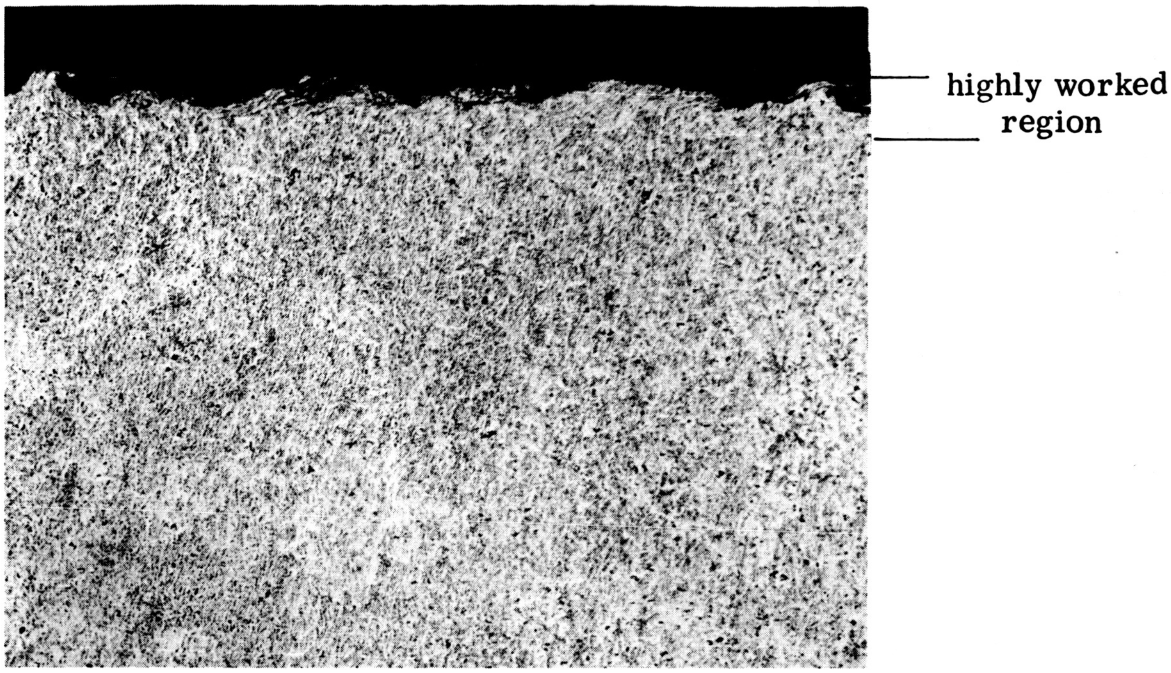
Figure -16

Figure 17a

Shows the appearance of a typical region of attack on the peened surface of the 7079-T651 ring exposed 60 days to alternate immersion. Despite the fact that this specimen was exposed four times that of the specimen shown below, the depth of attack is still confined primarily to the highly worked surface region.

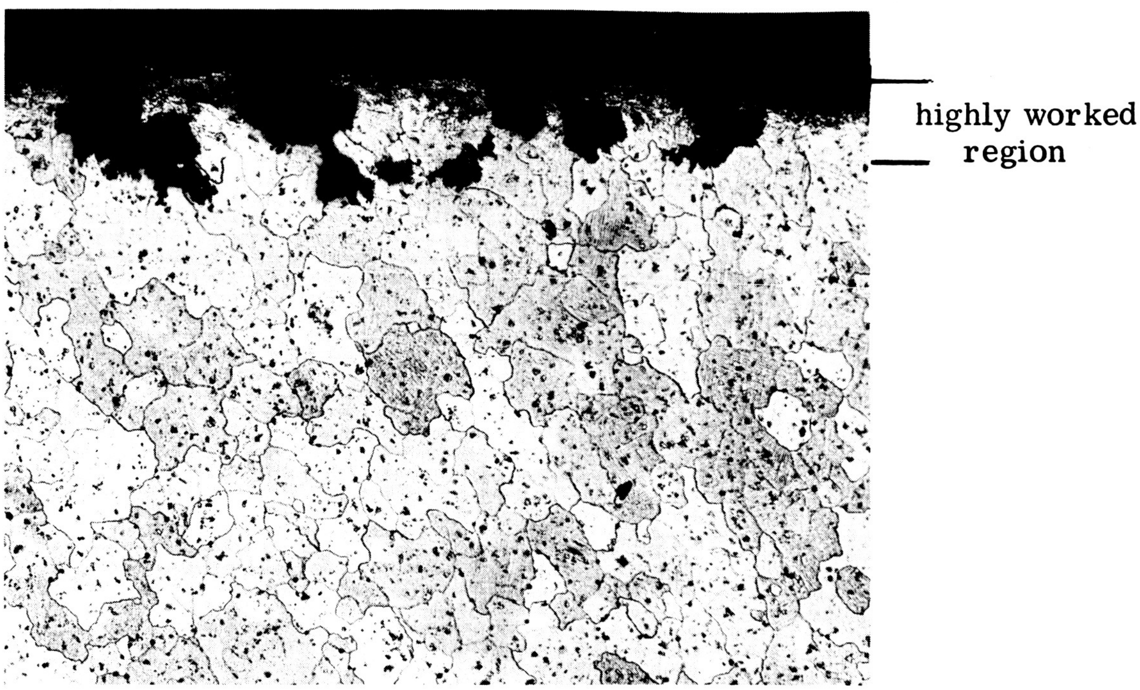
Figure 17b

Shows the appearance of a typical region of attack on the peened surface of the 2014-T651 ring exposed 60 days to alternate immersion. Depth of attack is well below the highly worked region (the top 1/4 to 5/16" of the picture). See also Figure 18.



S302354-2R5 Mag. 100X Etch: Keller's

Figure 17a



S302309-2R5 Mag. 100X Etch: Keller's

Figure 17b

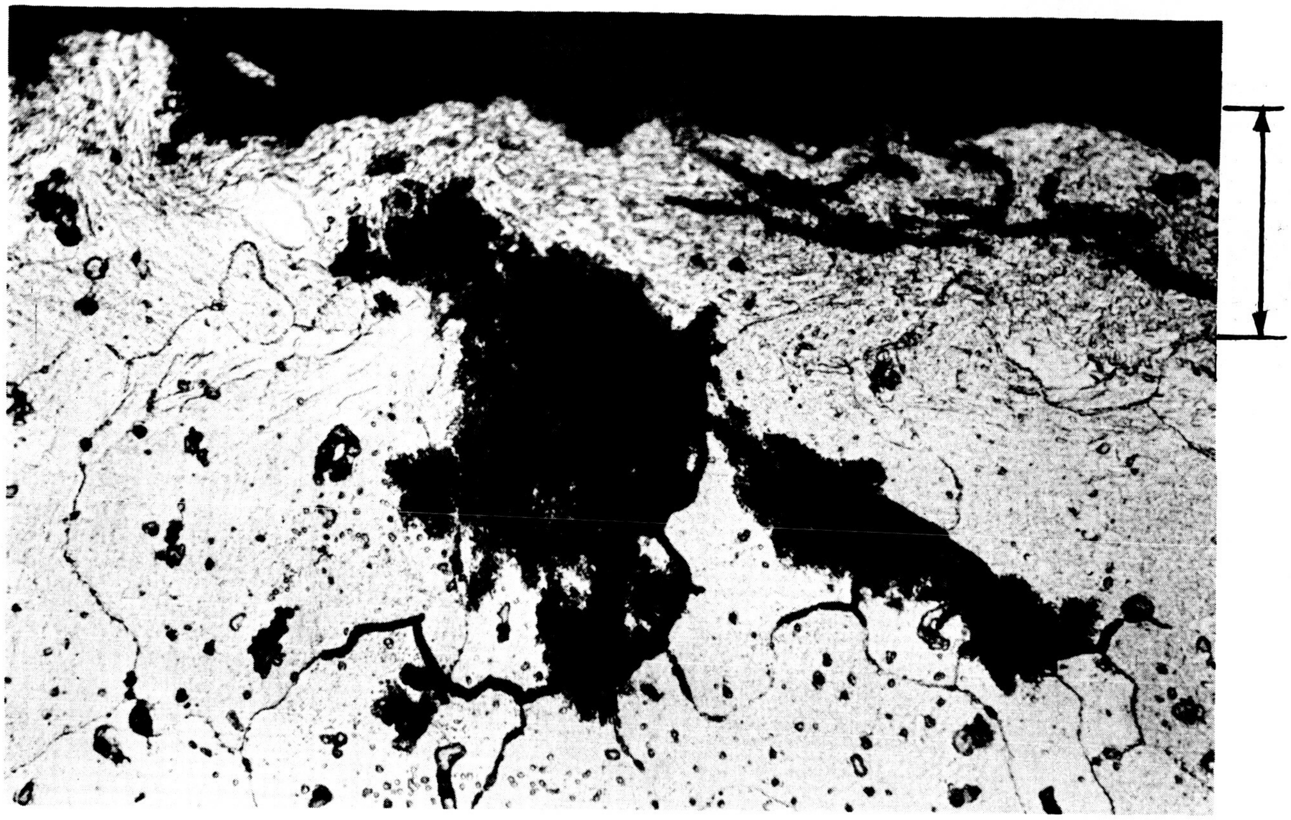
141087J
141091J

Figure 18a

Shows a portion of the region in Figure 17b at higher magnification to illustrate intergranular attack extending from pitting below the highly worked region.

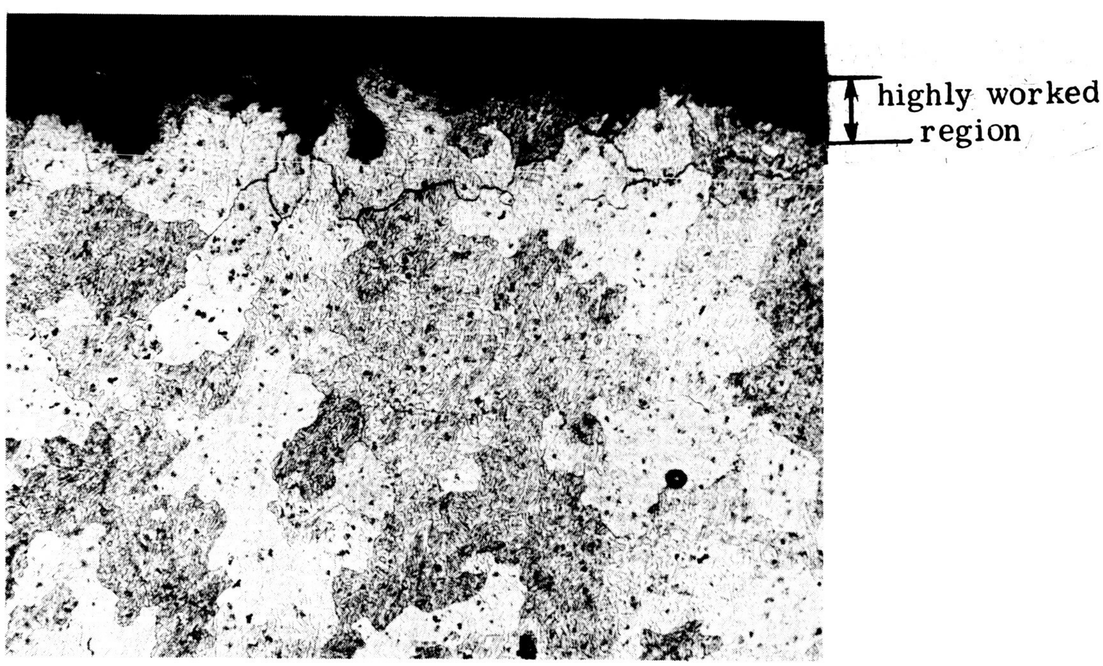
Figure 18b

Shows in cross section a typical region of attack on the peened surface of a 2024-T351 ring that failed after 18 days' alternate immersion in 3.5% NaCl. Note the pitting attack in the highly worked surface region and the intergranular attack extending below this.



S302309-2R5 Mag. 500X Etch: Keller's

Figure 18a



S302210-2R1 Mag. 100X Etch: Keller's

Figure 18b

14069J
14108AJ

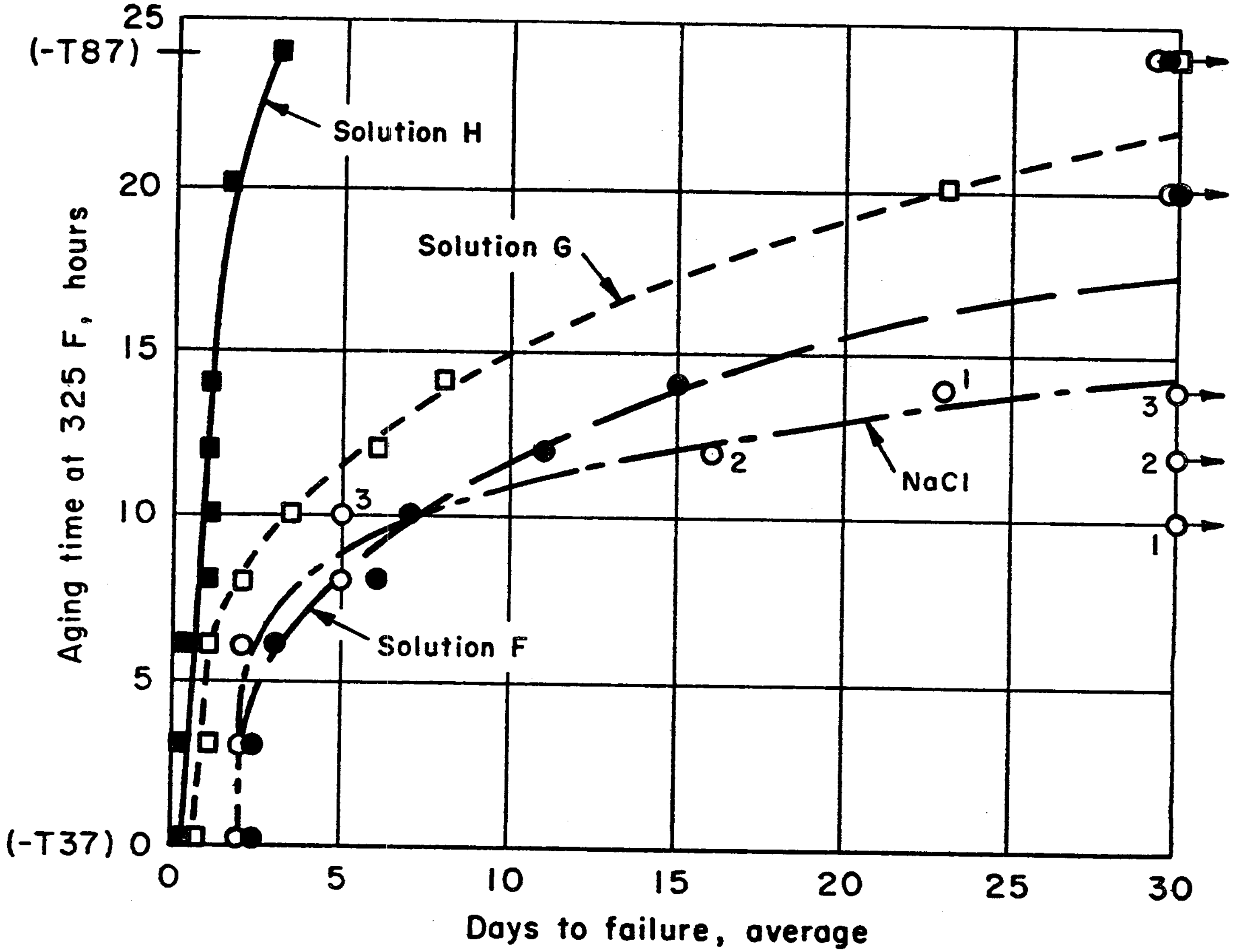


FIG. 19 – TRANSVERSE TENSILE BARS (0.125-IN. DIAM) OF 2219 ALLOY ROD STRESSED 75 % YIELD STRENGTH AND EXPOSED TO VARIOUS SOLUTIONS BY ALTERNATE IMMERSION

Figure 20

Neg. No. PDG197 Mag: 10X

Photograph of unstressed tensile bars (after chemical cleaning and tension tests).

2219-T37 aged 14 hours at 325°F

Top S - 320215 -T13 - Exposed 23 days in 3.5% NaCl electrolyte, 22% loss in T.S.

Bottom S - 320215 -T18 - Exposed 7 days in "G" electrolyte, 10% loss in T.S.

It was noted in Figure 19 that 7 days' alternate immersion in electrolyte "G" was just as effective in causing stress-corrosion cracking as 30 days in 3.5% NaCl.

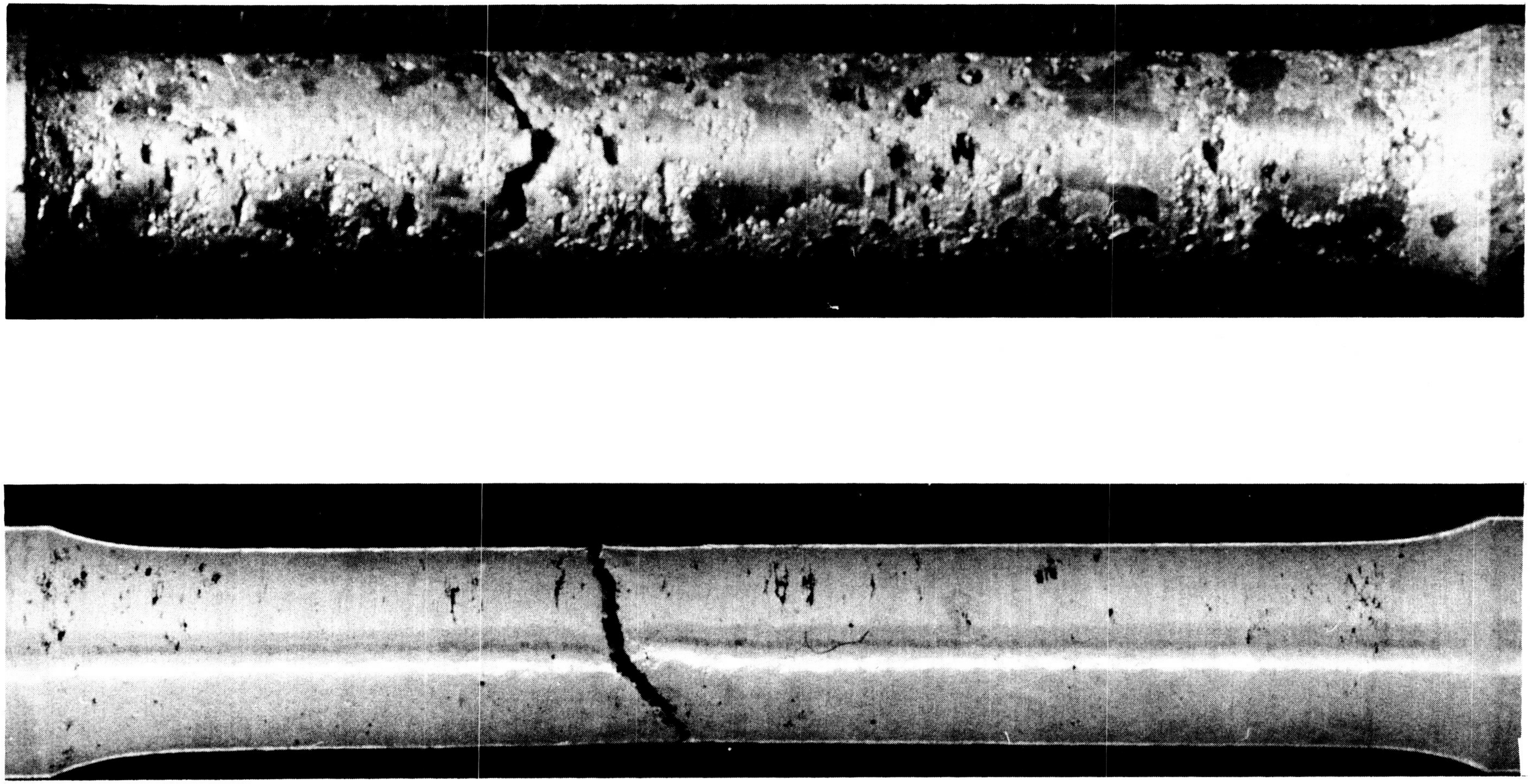


Figure -20

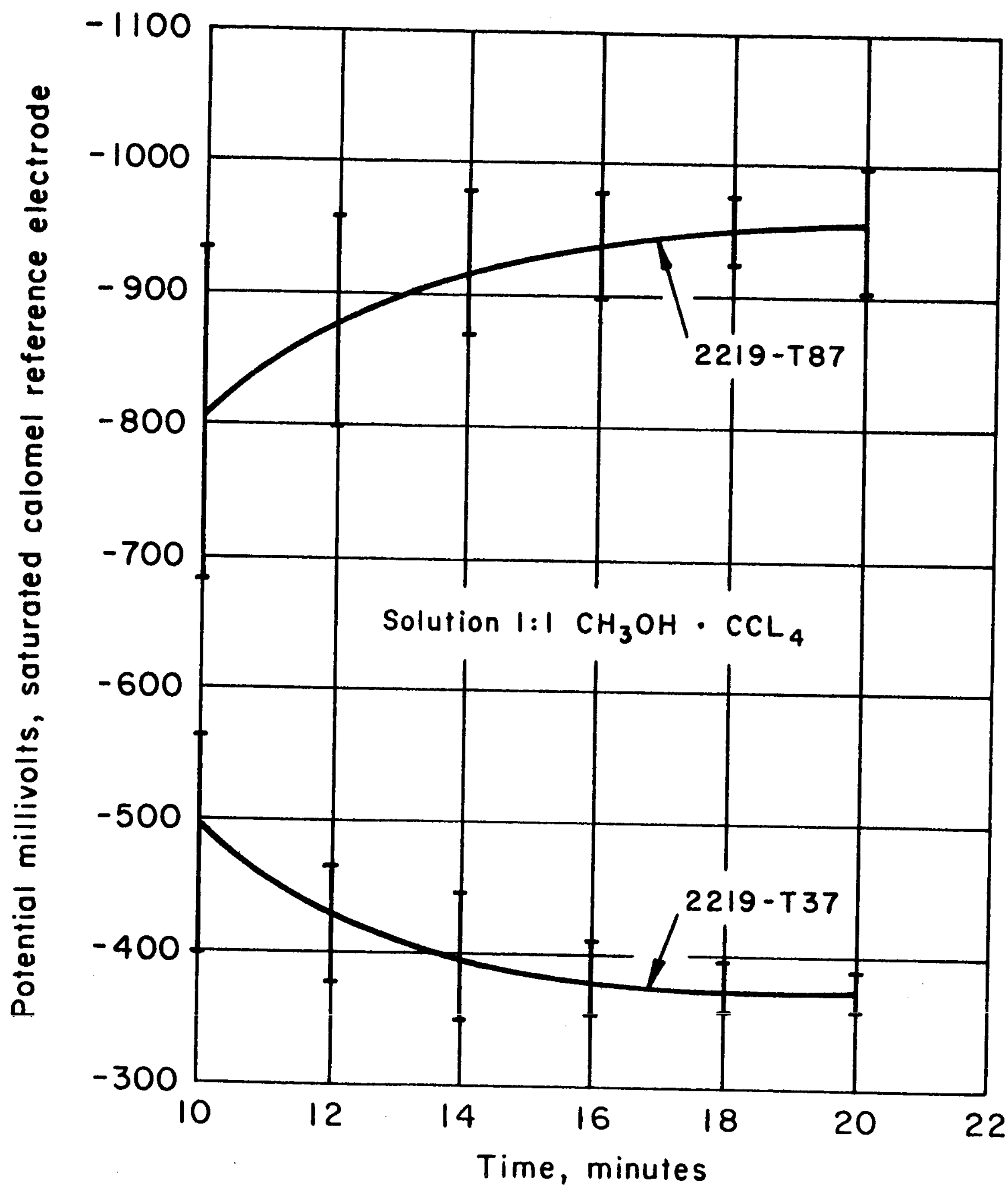


FIG. 21 – POTENTIAL-TIME CURVES FOR 2219-T37 AND -T87 ROD SHOWING AVERAGE OF 10 MEASUREMENTS AND SCATTER OF DATA AT VARIOUS TIMES

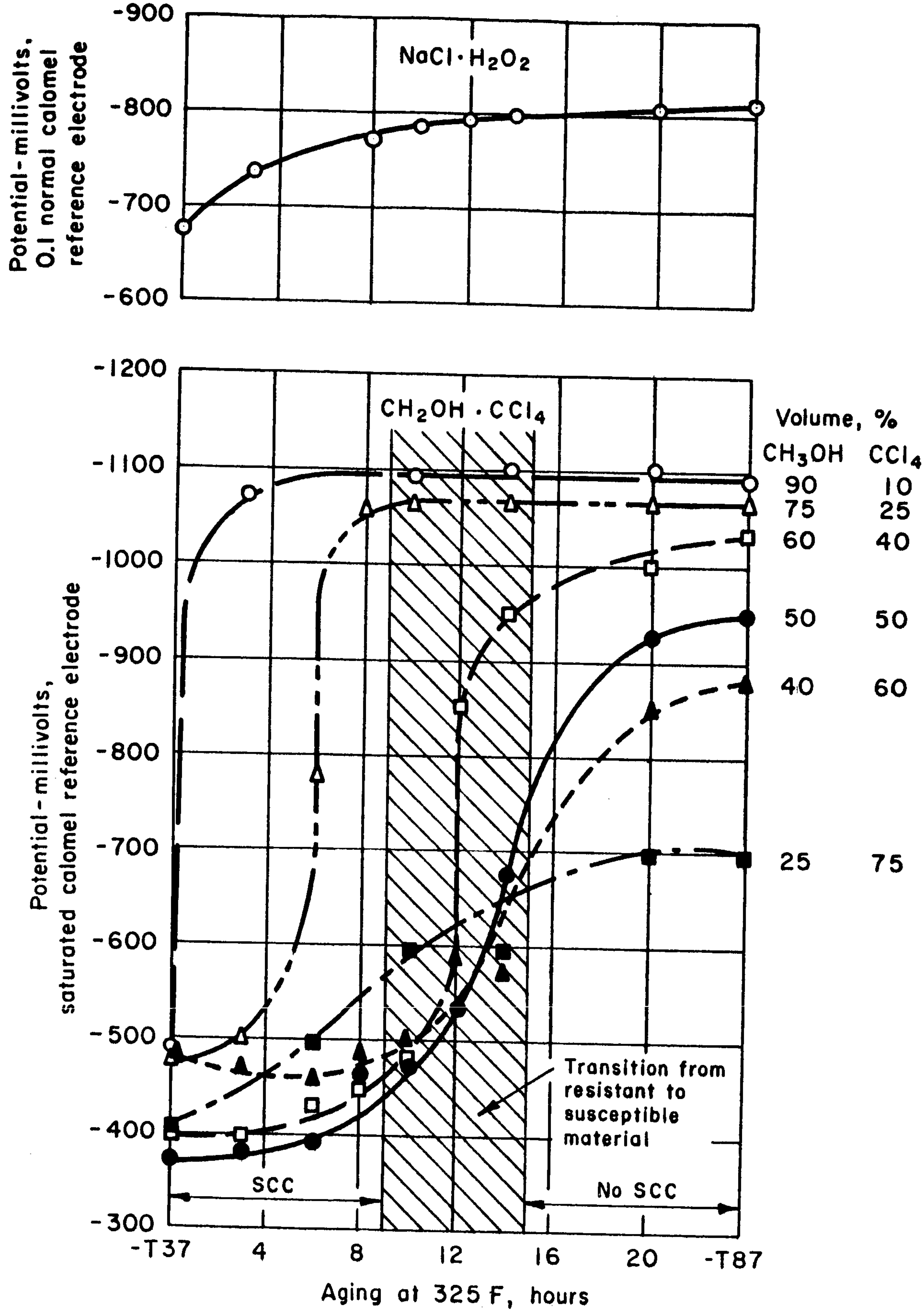


FIG. 22 – EFFECT OF METHYL ALCOHOL-CARBON TETRACHLORIDE VOLUME RATIO ON AGING-POTENTIAL CURVE 2219-T87 TEMPER ROD (2 1/2-IN. DIAM 2219-T37 ROLLED ROD)

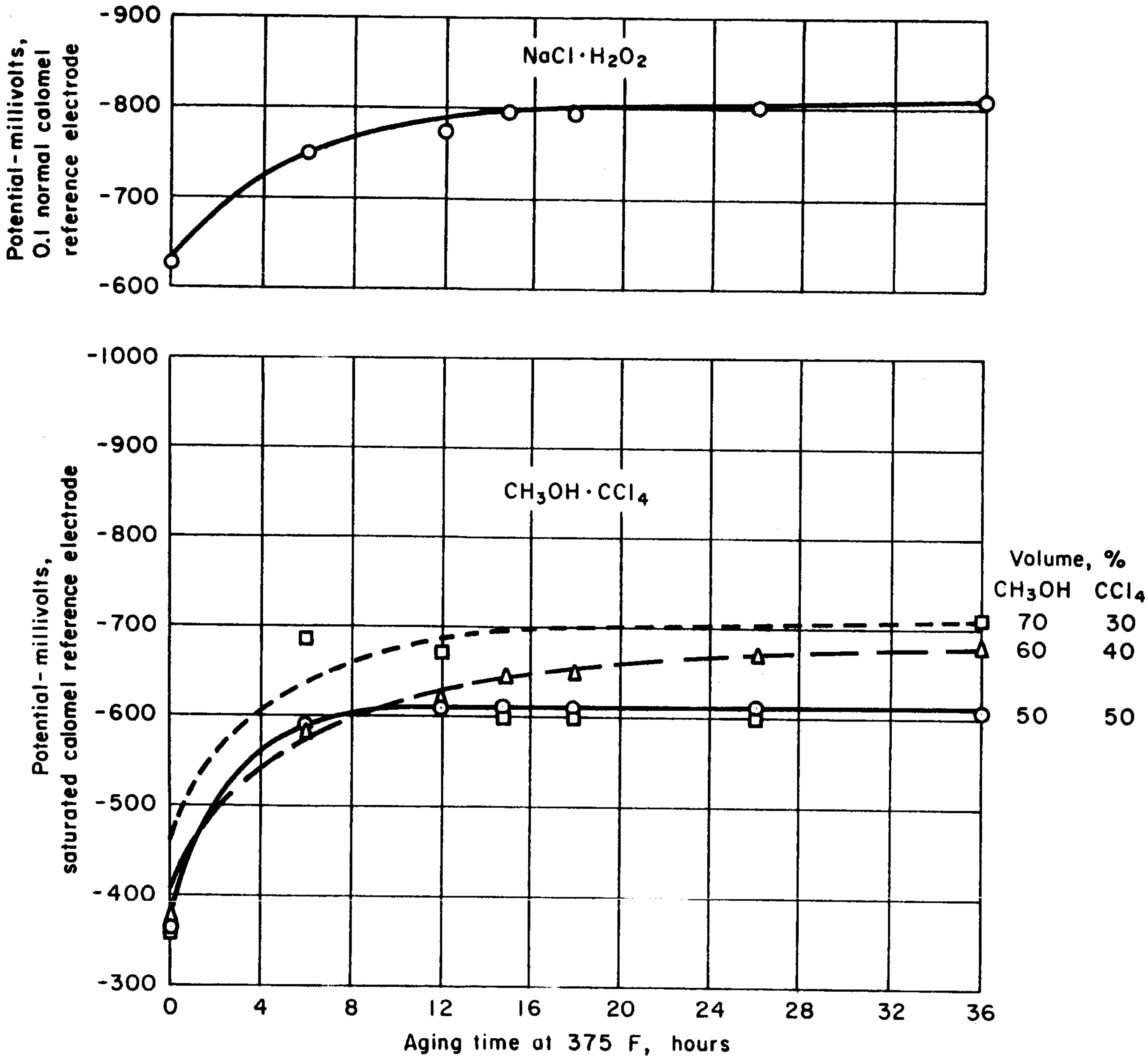


FIG. 23 – AGING-POTENTIAL CURVES FOR 2219-T6 DIE FORGING
2219-T4 DIE FORGED ELBOW

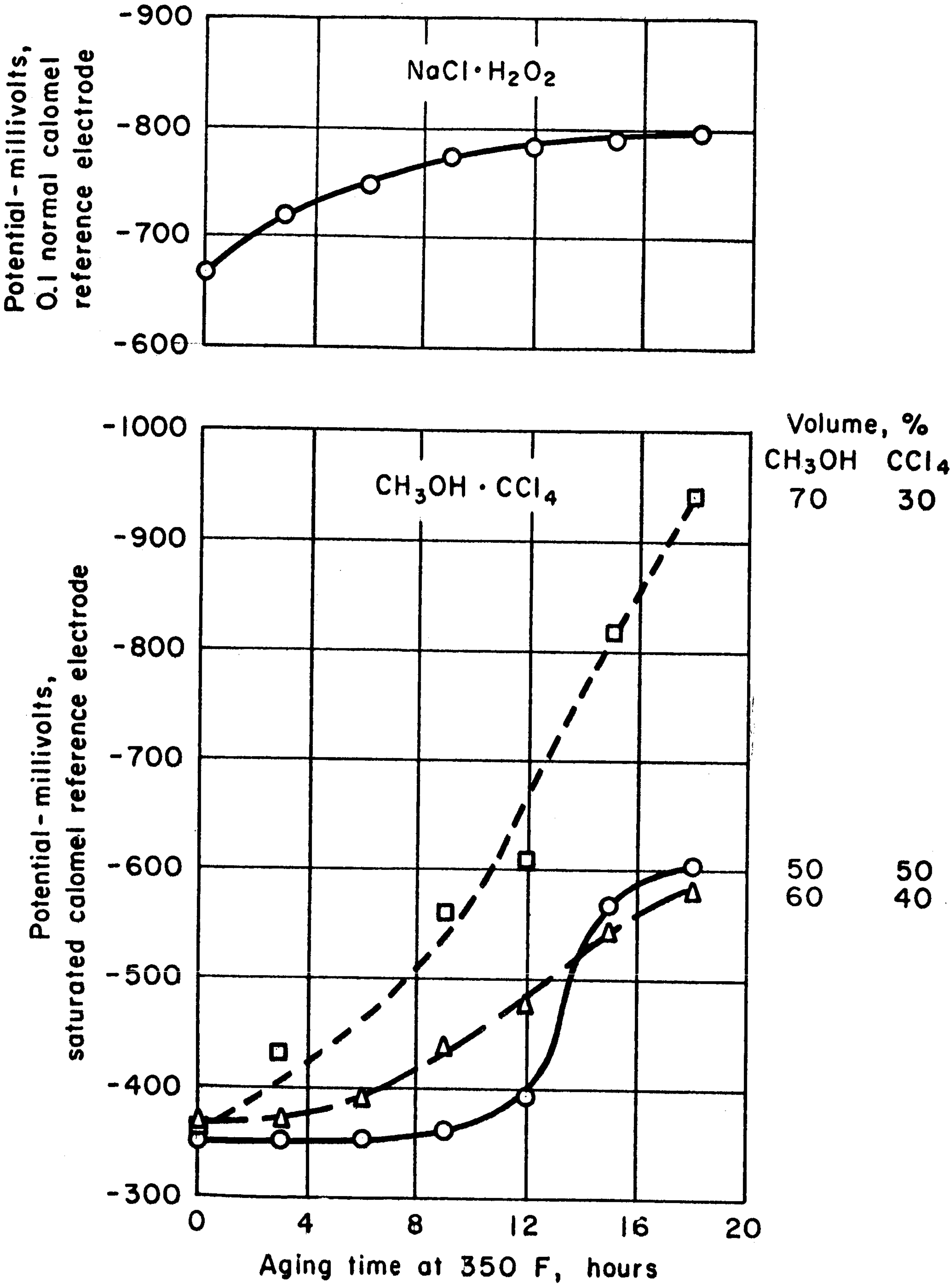


FIG. 24 – AGING-POTENTIAL CURVES FOR 2219-T851 PLATE
4-IN. THICK 2219-T351 PLATE (CENTER)

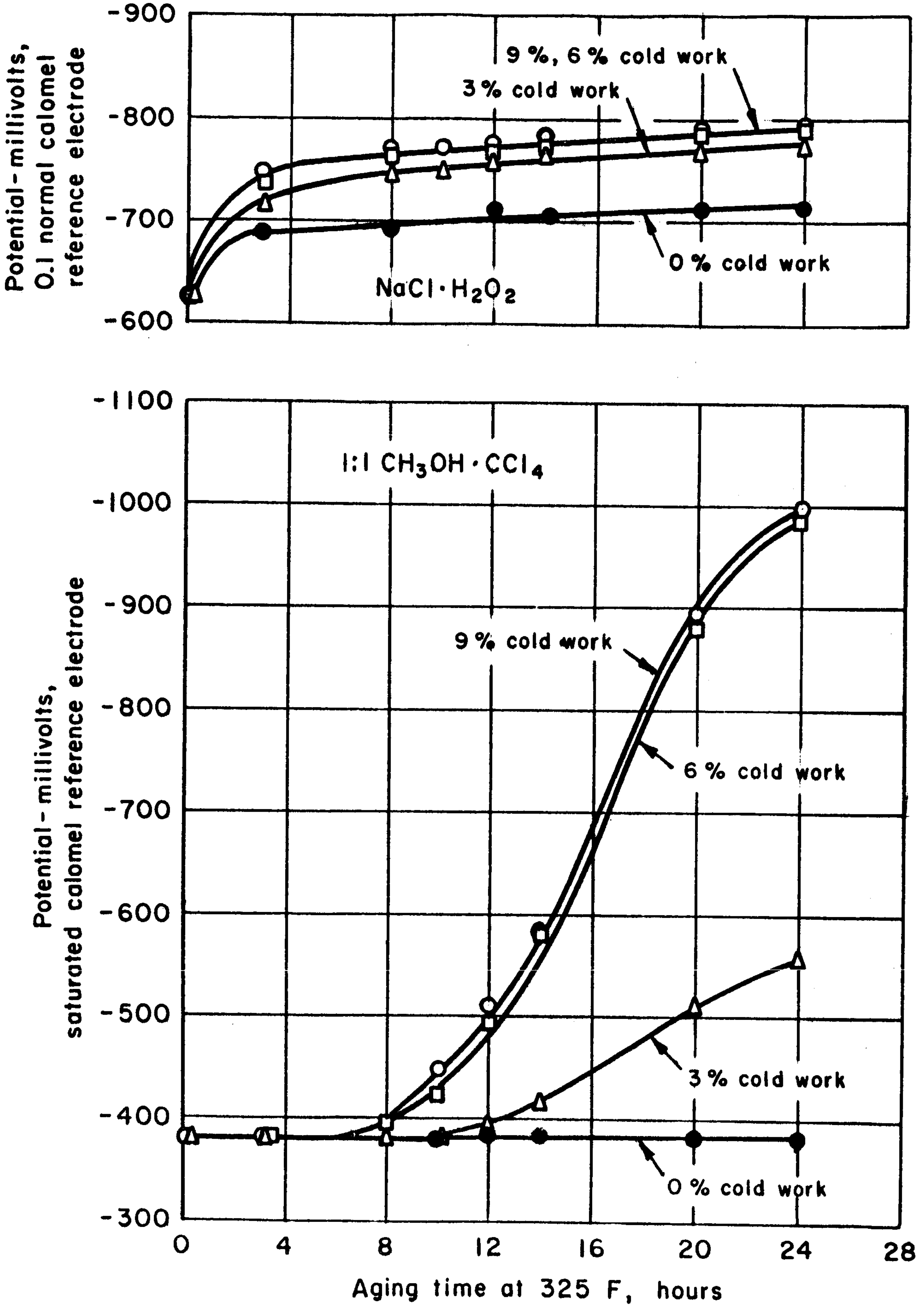


FIG. 25 — AGING-POTENTIAL CURVES FOR 2219 ALLOY SHOWING EFFECT OF COLD WORK

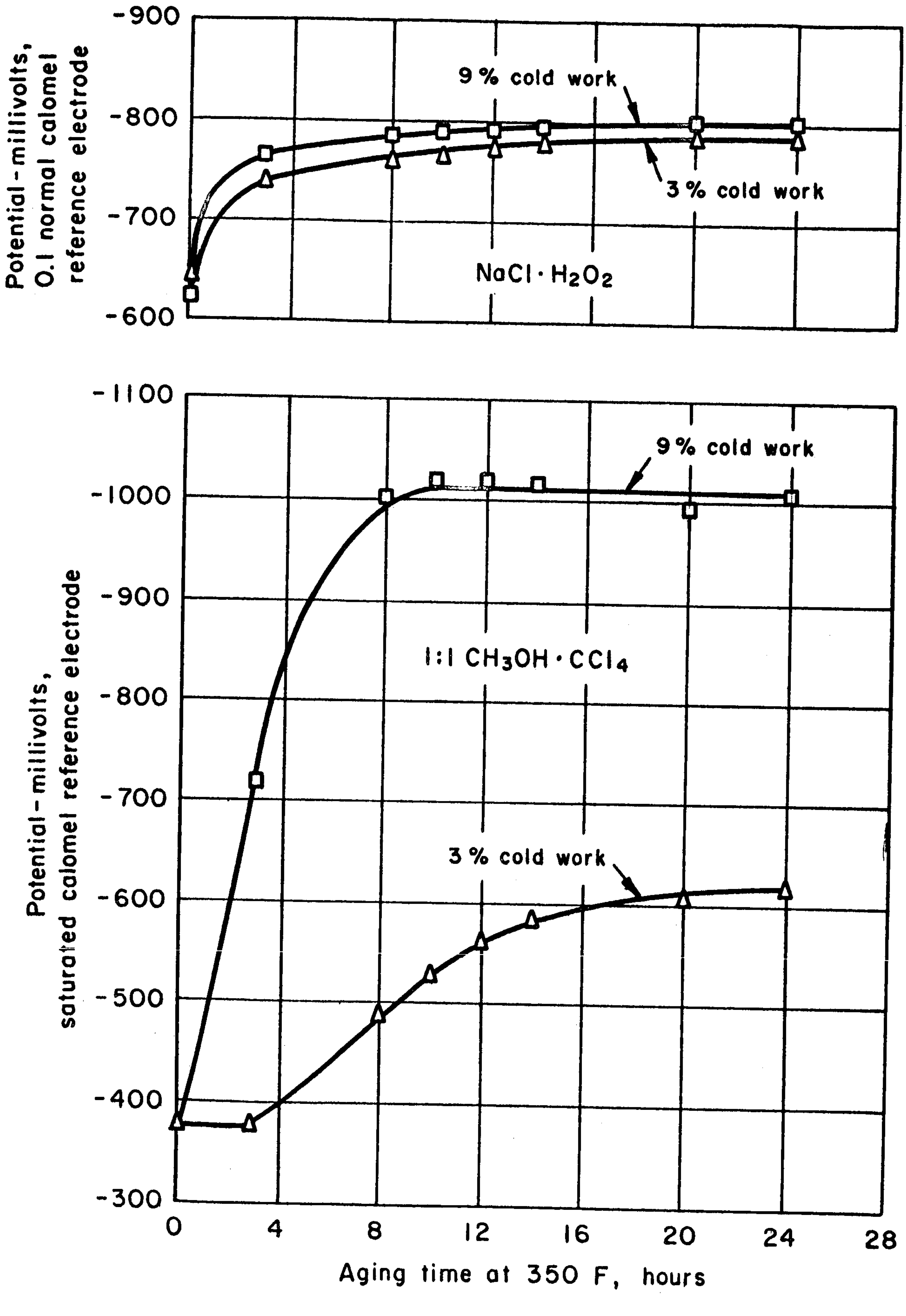


FIG. 26 – AGING-POTENTIAL CURVES FOR 2219 ALLOY SHOWING EFFECT OF COLD WORK

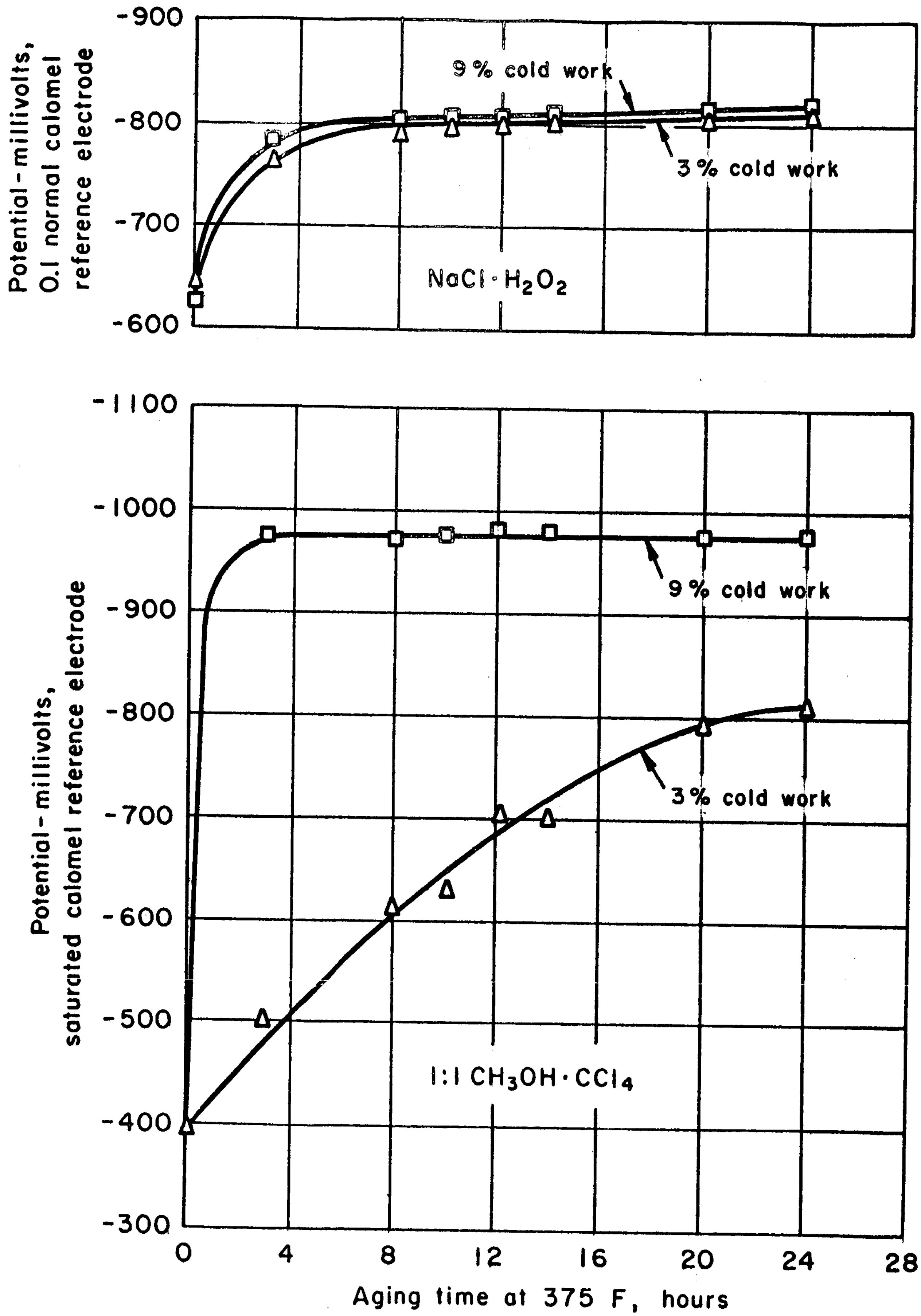
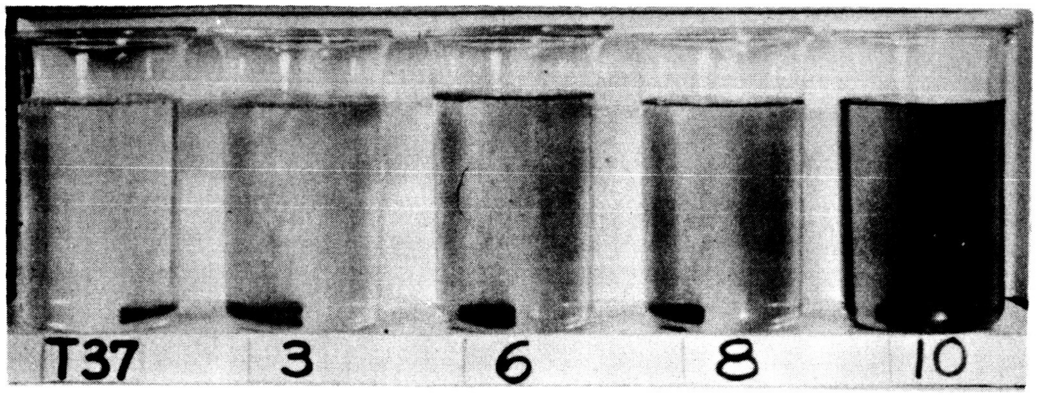
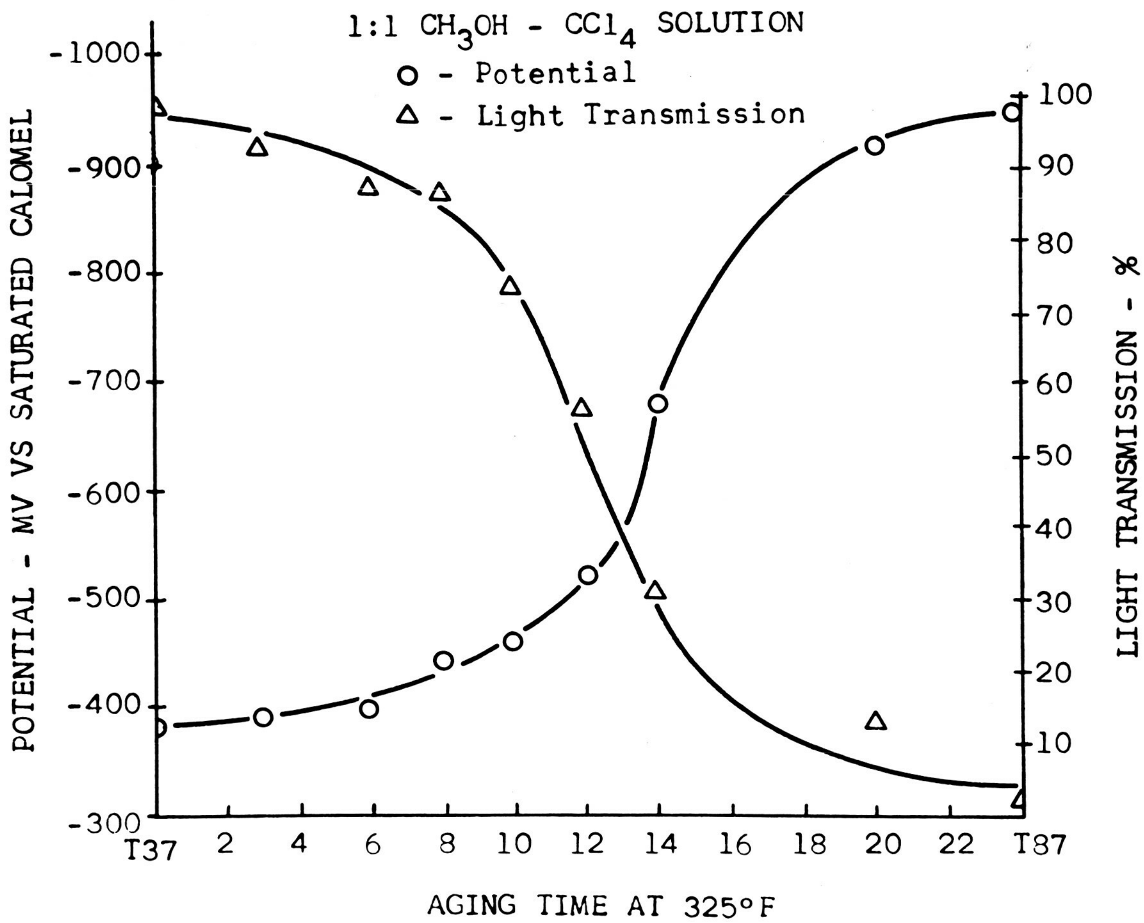


FIG. 27 — AGING-POTENTIAL CURVES FOR 2219 ALLOY SHOWING EFFECT OF COLD WORK





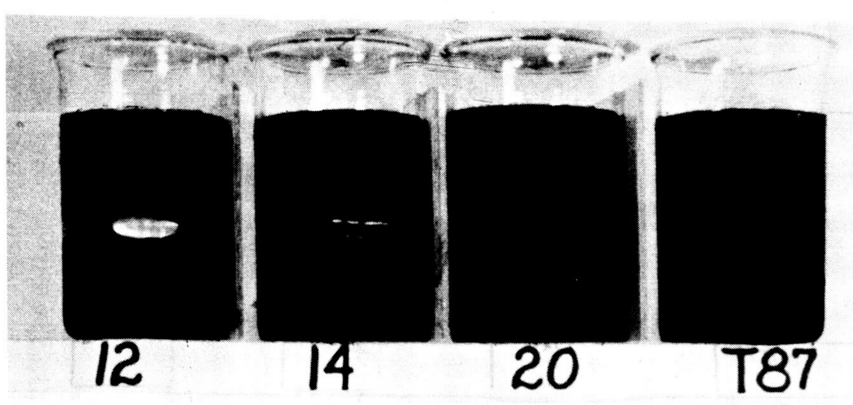
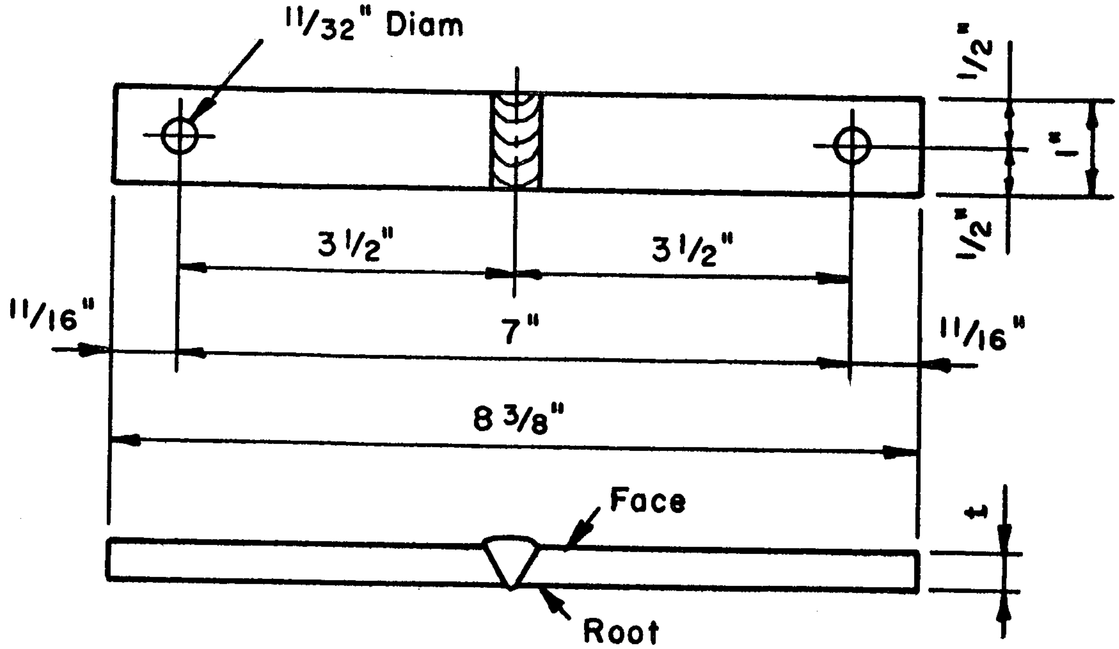
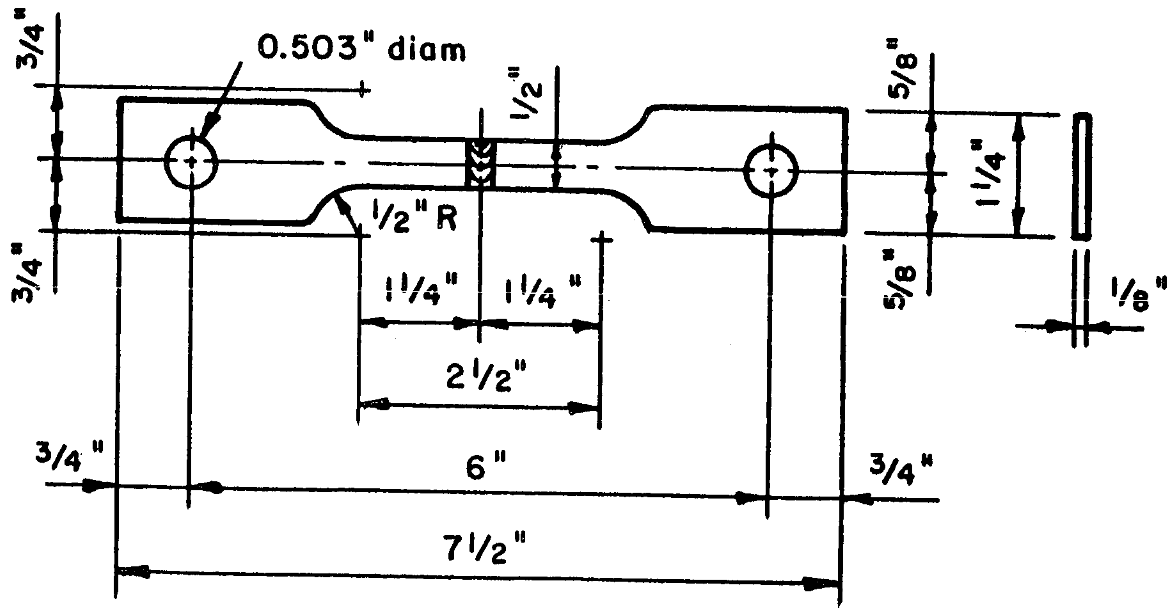


Figure -28

PDE000CJ

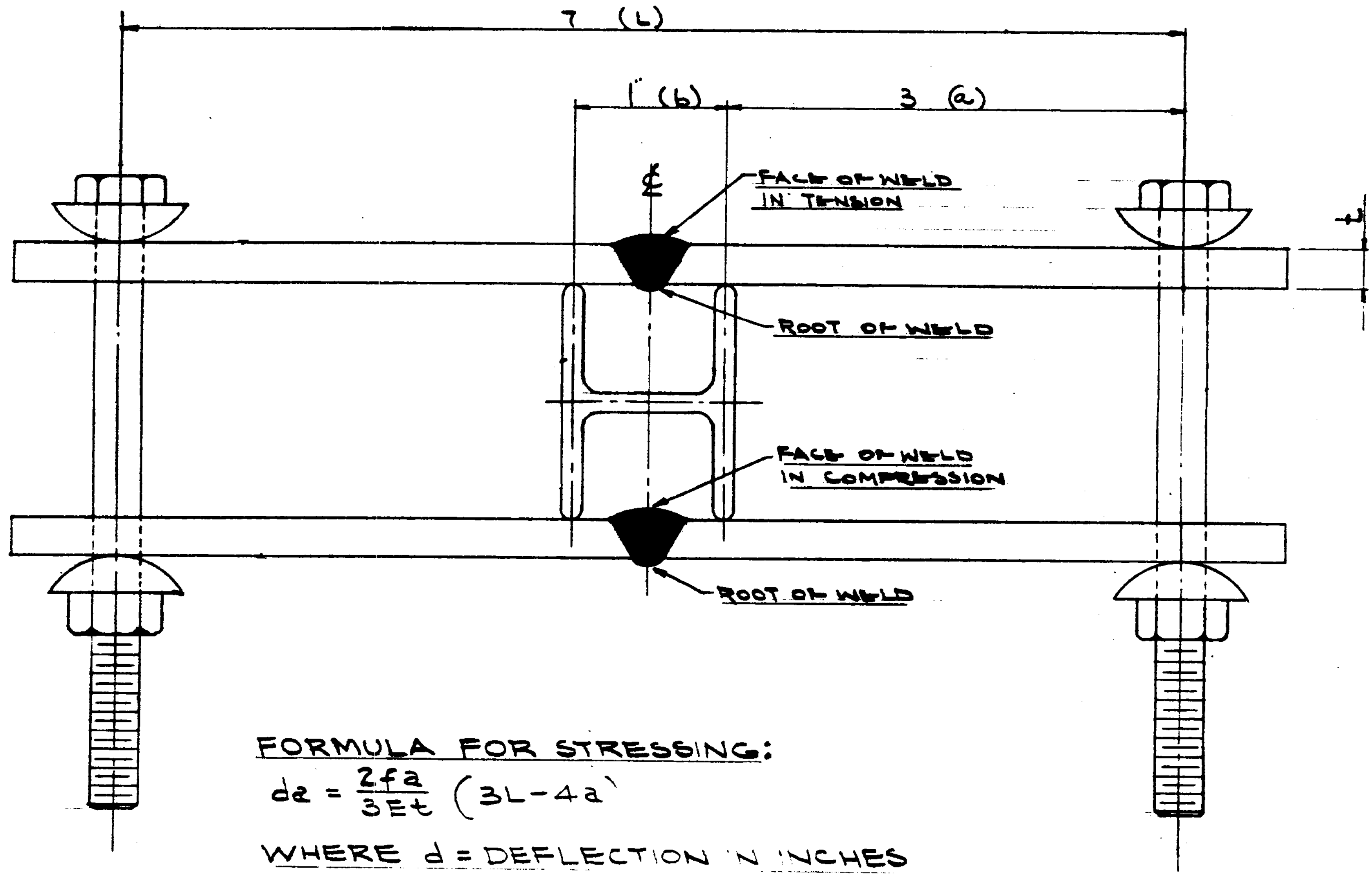


WELDED BEAM STRESS CORROSION SPECIMEN



WELDED SHEET TENSILE SPECIMEN

FIG. 29



FORMULA FOR STRESSING:

$$d_a = \frac{2fa}{3Et}\left(3L - 4a\right)$$

WHERE d = DEFLECTION IN INCHES
f = STRESS, PSI
E = MODULUS OF ELASTICITY

FIGURE 30 - BEAM STRESS CORROSION ASSEMBLY

PDB163J

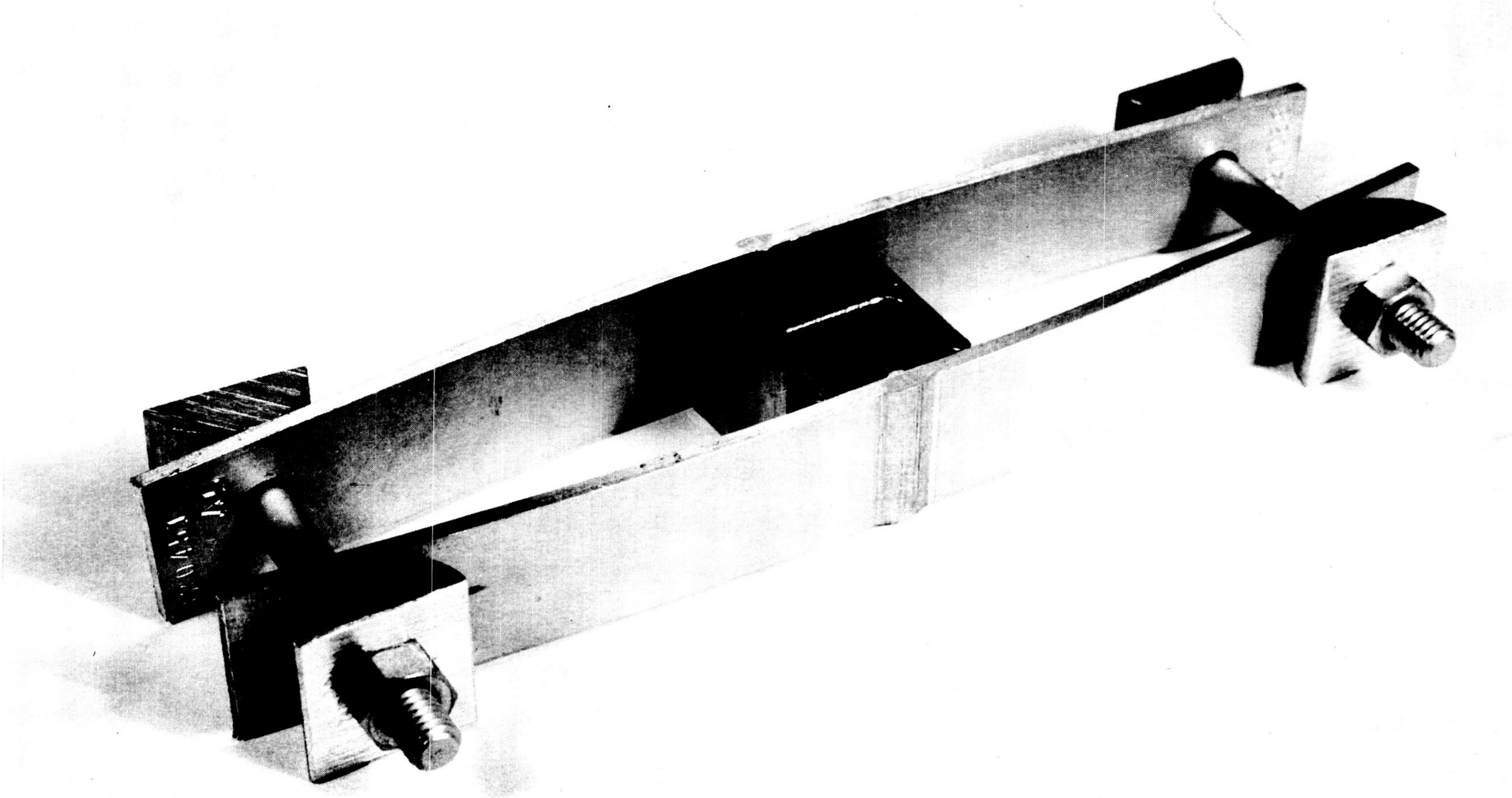


Figure 31 - Beam stress corrosion assembly used to stress 0.125" thick welded specimens in bending by constant deformation

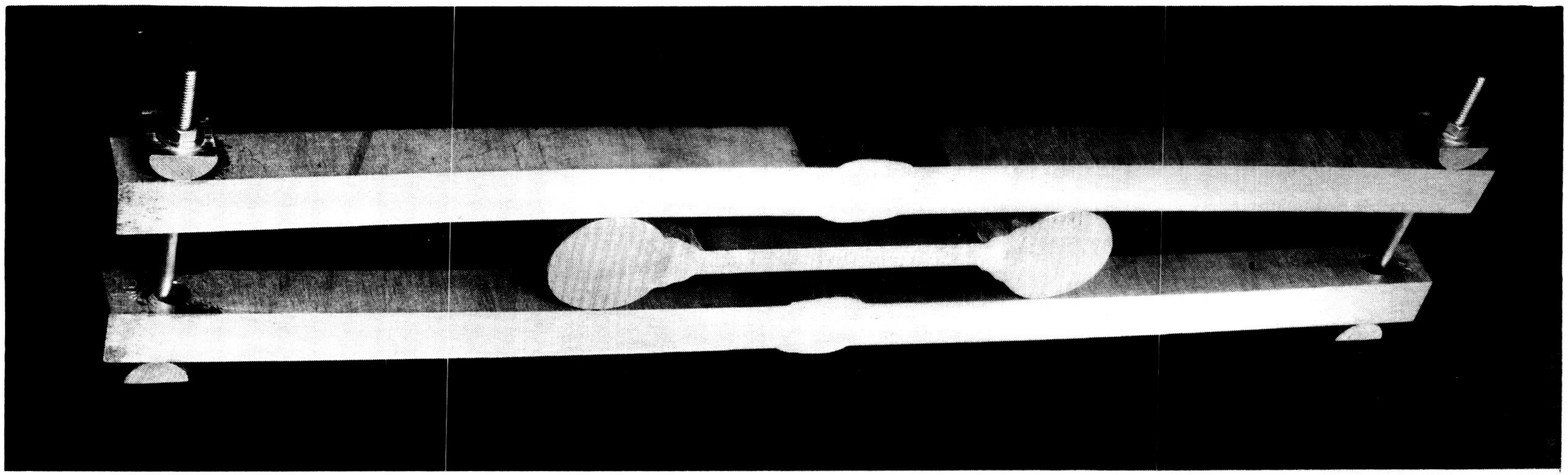
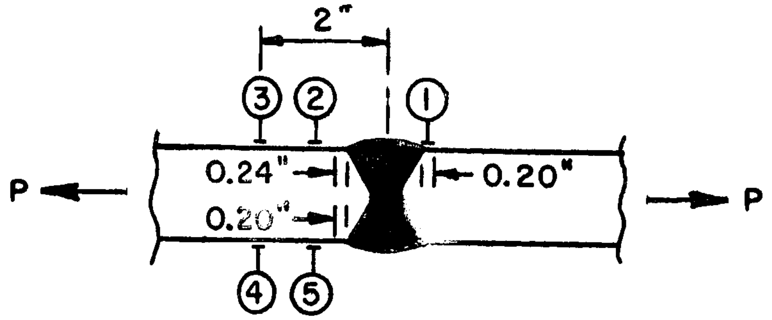


Figure 32 - Beam stress corrosion assembly used to stress 1.0" thick welded specimens in bending by constant deformation



Location of foil type C12-121 electrical strain gauges

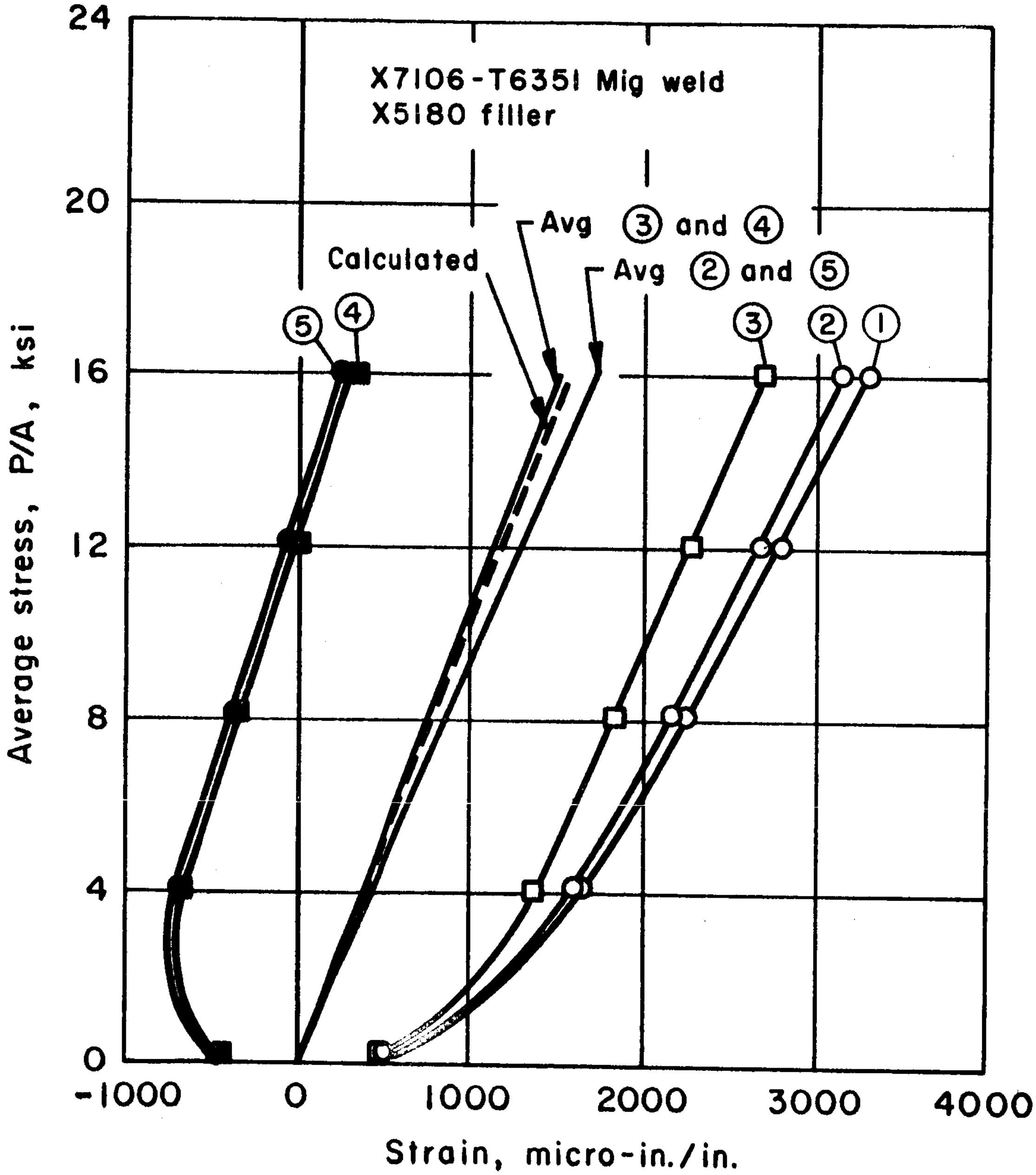
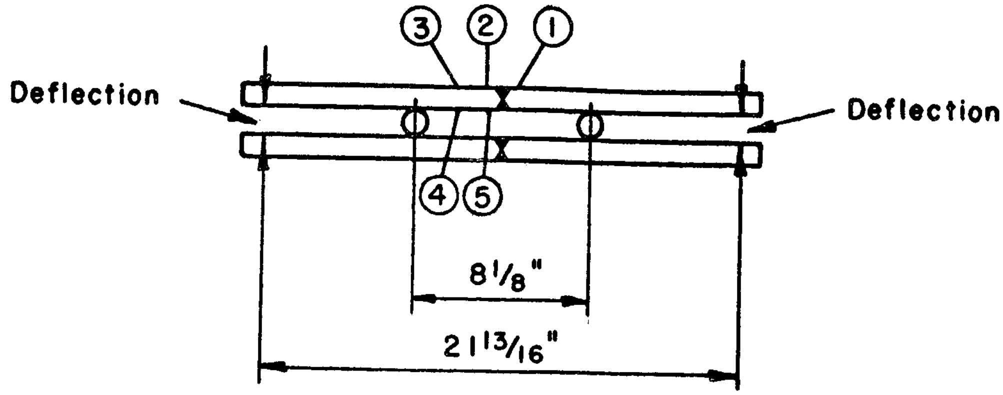


FIG. 33 – SURVEY OF VARIATIONS OF STRESS IN THE HEAT AFFECTED ZONE OF MIG WELDED 1-IN. THICK PLATE X7106-T6351 DURING TENSILE LOADING



Location of foil type C12-121 electrical strain gauges

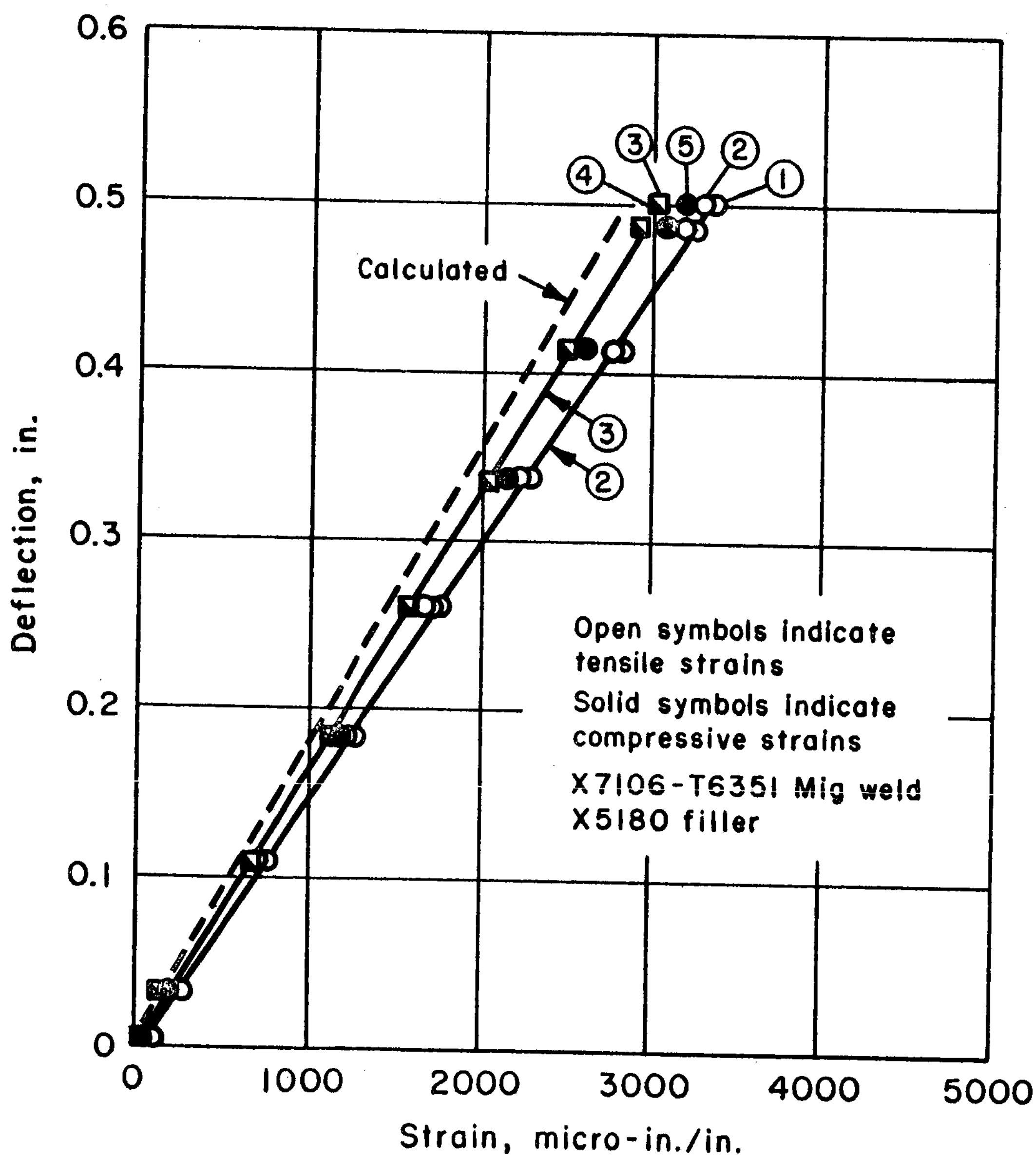


FIG. 34 — SURVEY OF VARIATIONS IN STRAIN IN THE HEAT AFFECTED ZONE OF MIG WELDED 1-IN. THICK PLATE DURING BENDING OF BEAM TYPE STRESS-CORROSION SPECIMEN

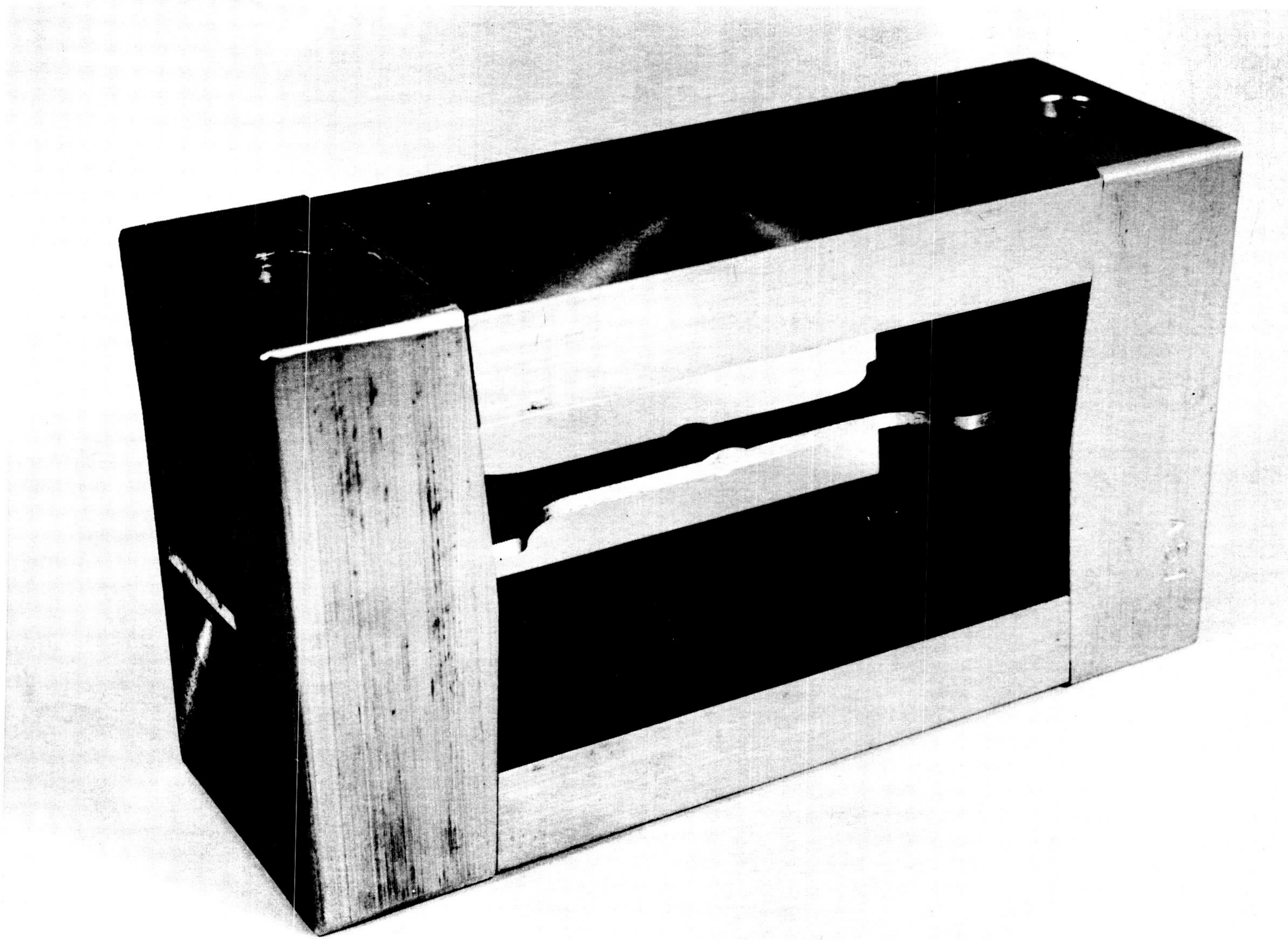


Figure 35 - Constant deformation type fixture used to stress 0.125" thick sheet tensile specimens in direct tension

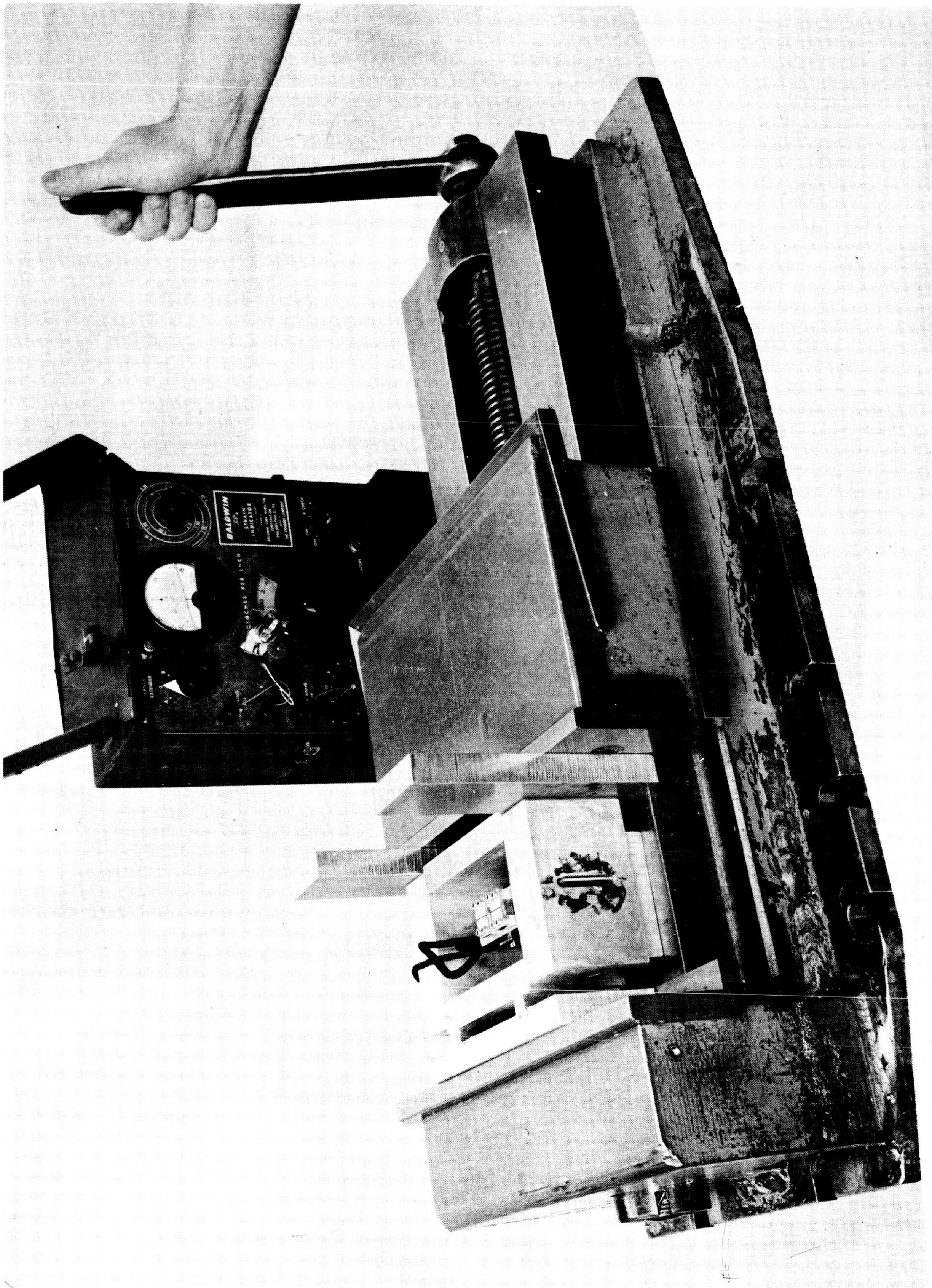


Figure -36

PDB063J

Figure 36

Illustrates loading of welded sheet specimens in constant deformation fixture with an electrical strain gauge. In both types of fixtures (constant deformation and constant load) the strain equivalent to the desired stress was measured over a half inch gauge length by means of an electrical strain gauge to $\pm$ 1 micro-inch placed adjacent to the weld heat affected zone.

PCK016J

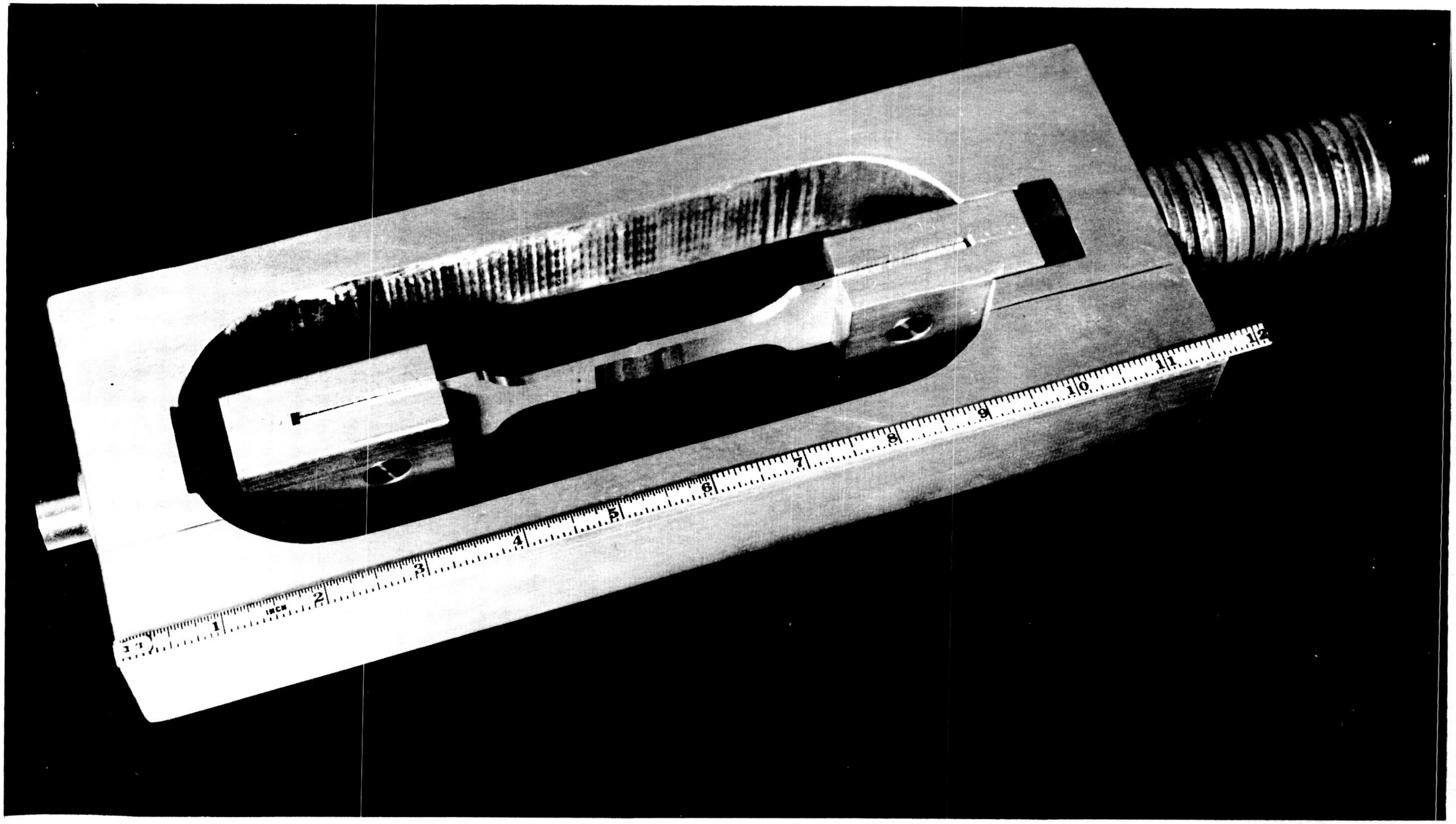
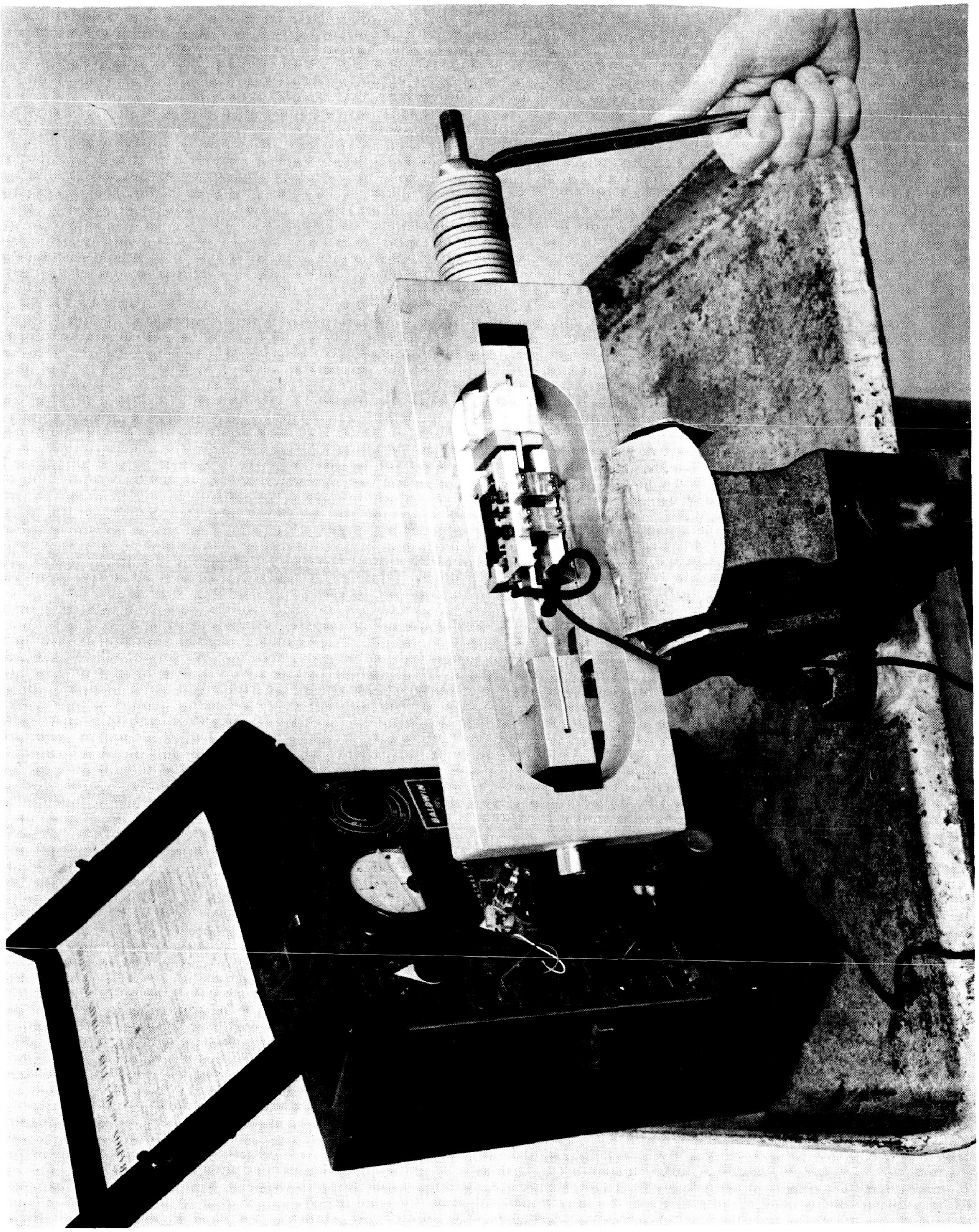


Figure 37 - Constant load type of fixture used to stress 0.125" thick sheet tensile specimens in direct tension

Figure 38

Illustrates loading of welded sheet specimens in constant load fixture with an electrical strain gauge in the same manner described on Figure 36. The Belleville Springs underneath the tightening nut provide essentially a constant load arrangement, giving the fixture a stiffness factor of only 1.3×10^4 lb./in. for the constant deformation fixture (Figures 35 and 36).



PDB062J

Figure -38

PDG002CJ

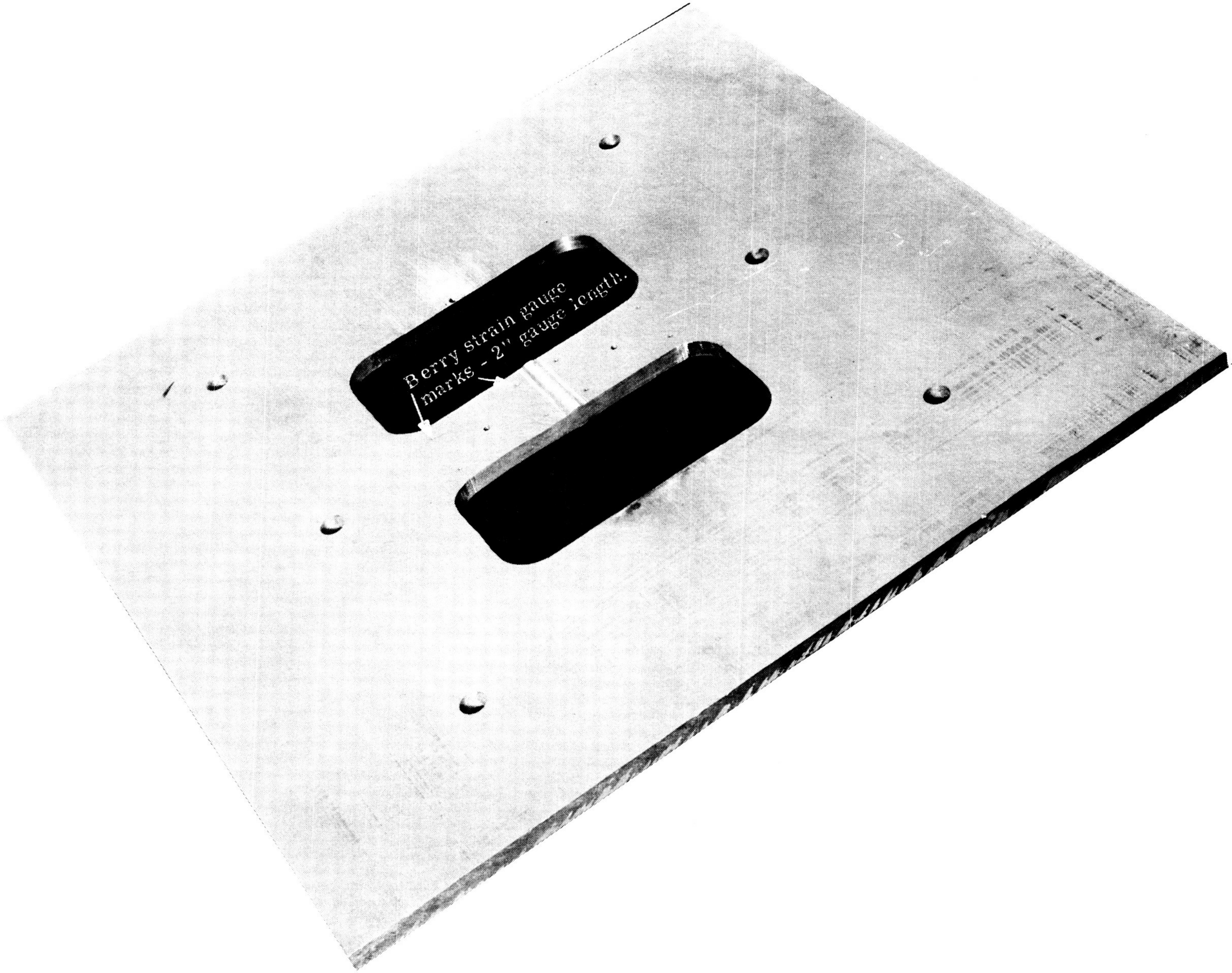


Figure 39 - Typical H-Plate specimen for stress corrosion tests of weldments

PDB023J

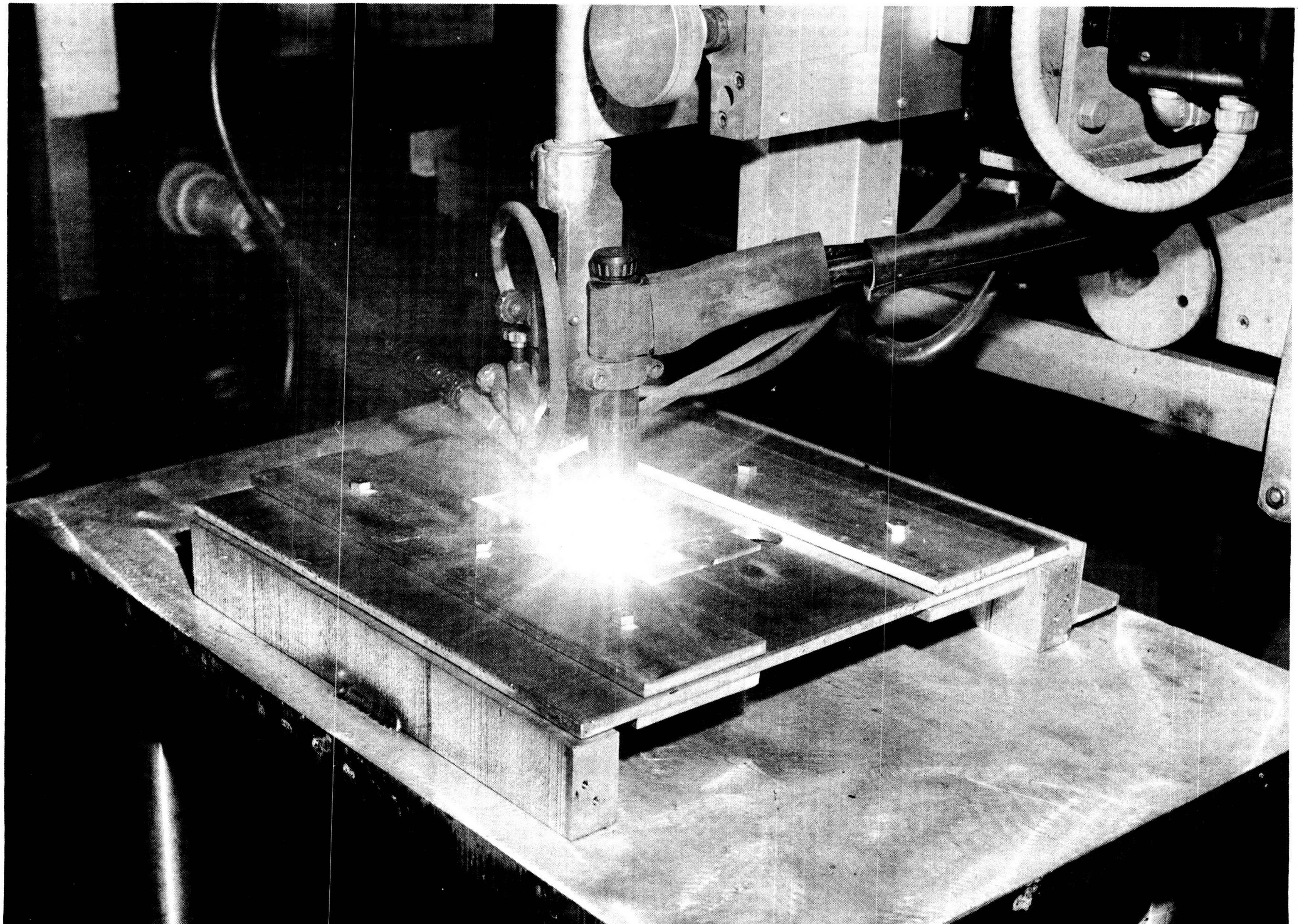


Figure 40 - Welding of H-plate specimen

Figure 41

Alternate immersion test equipment illustrates the manner in which the contract specimens were exposed. Specimens shown here in the "up" position were lowered into the tank of 3.5% NaCl solution for 10 minutes and then raised and allowed to dry for 50 minutes every hour.

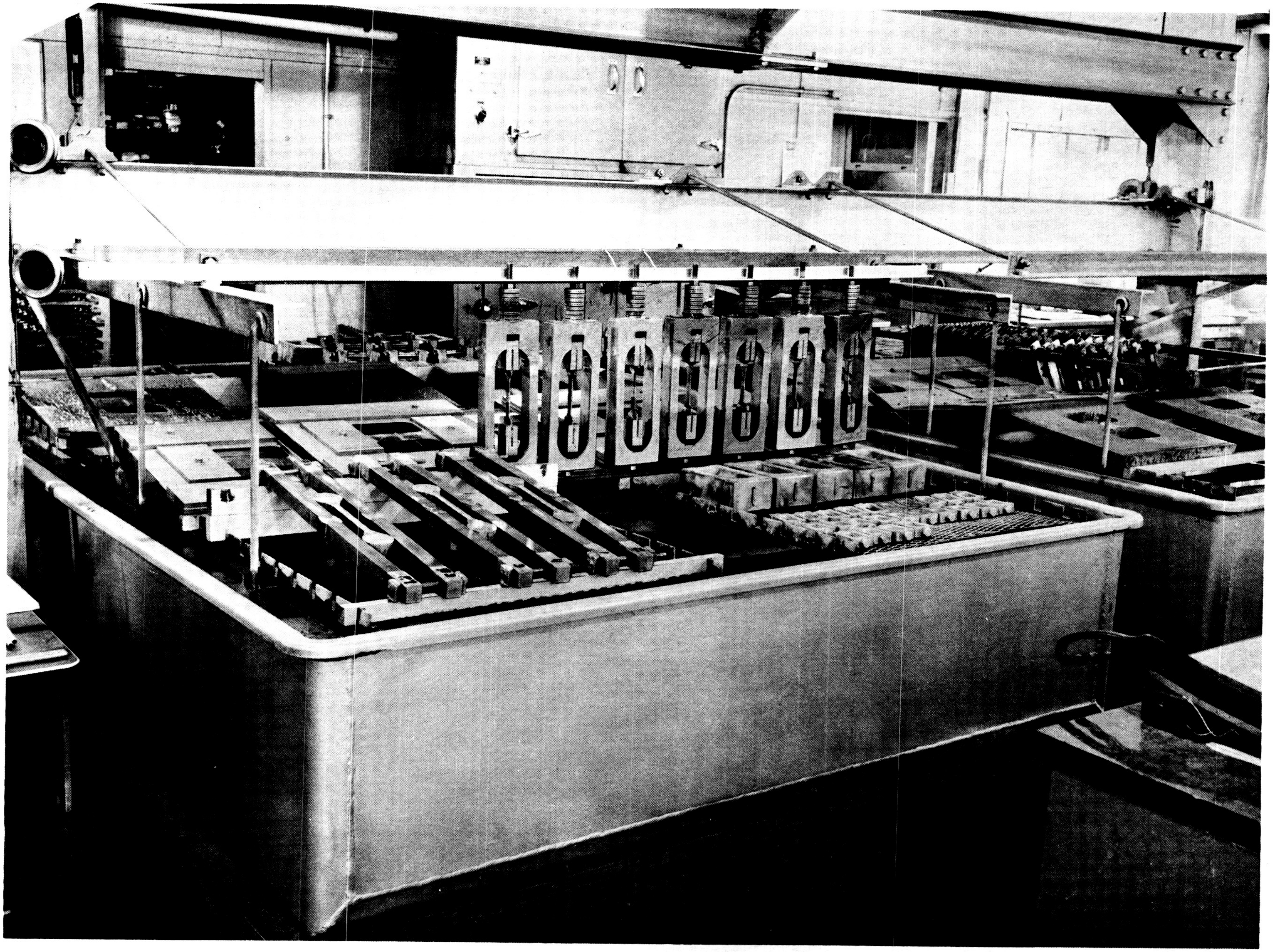


Figure -41

Figure 42

Mag: 3/4X

Illustrates appearance of DCSP-TIG welded 1/8" thick sheet specimens exposed three months in the 3.5% NaCl solution by alternate immersion. Upper specimen in each pair shows face of weld bead and lower specimen shows the penetration bead. (Corrosion products removed by immersion in concentrated nitric acid.)

% Losses in tensile strength caused by corrosion were as follows:

S. No.	Alloy	Parent Sheet	As Welded (1)
320444	X7106-T6	0	15
320451	X7139-T6	0	17
320449	7039-T6	0	19
320447	X7002-T6	2	16

(1) X5180 filler wire except for 7039-T6 which had 5183.

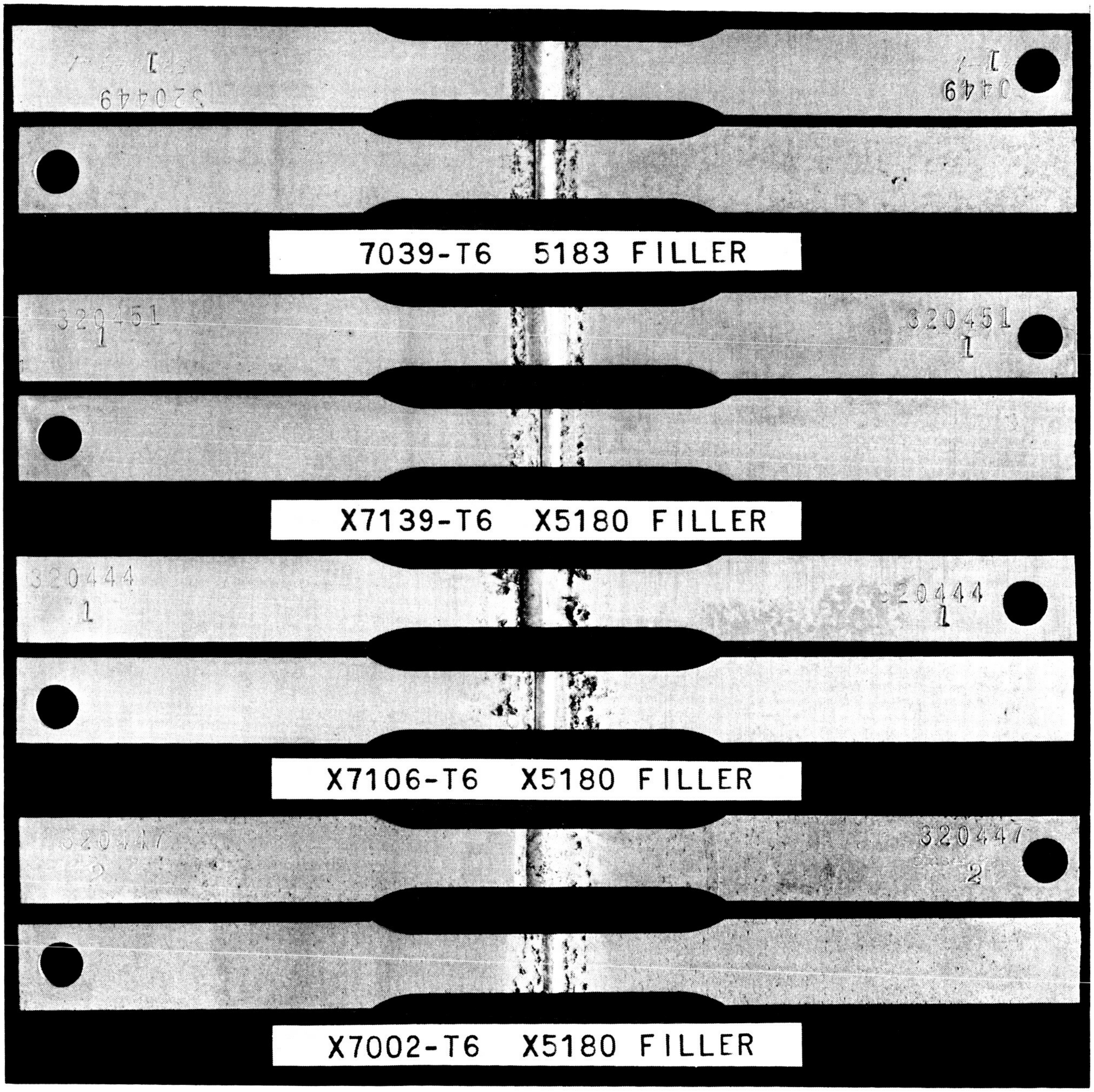


Figure -42

PDG097CJ

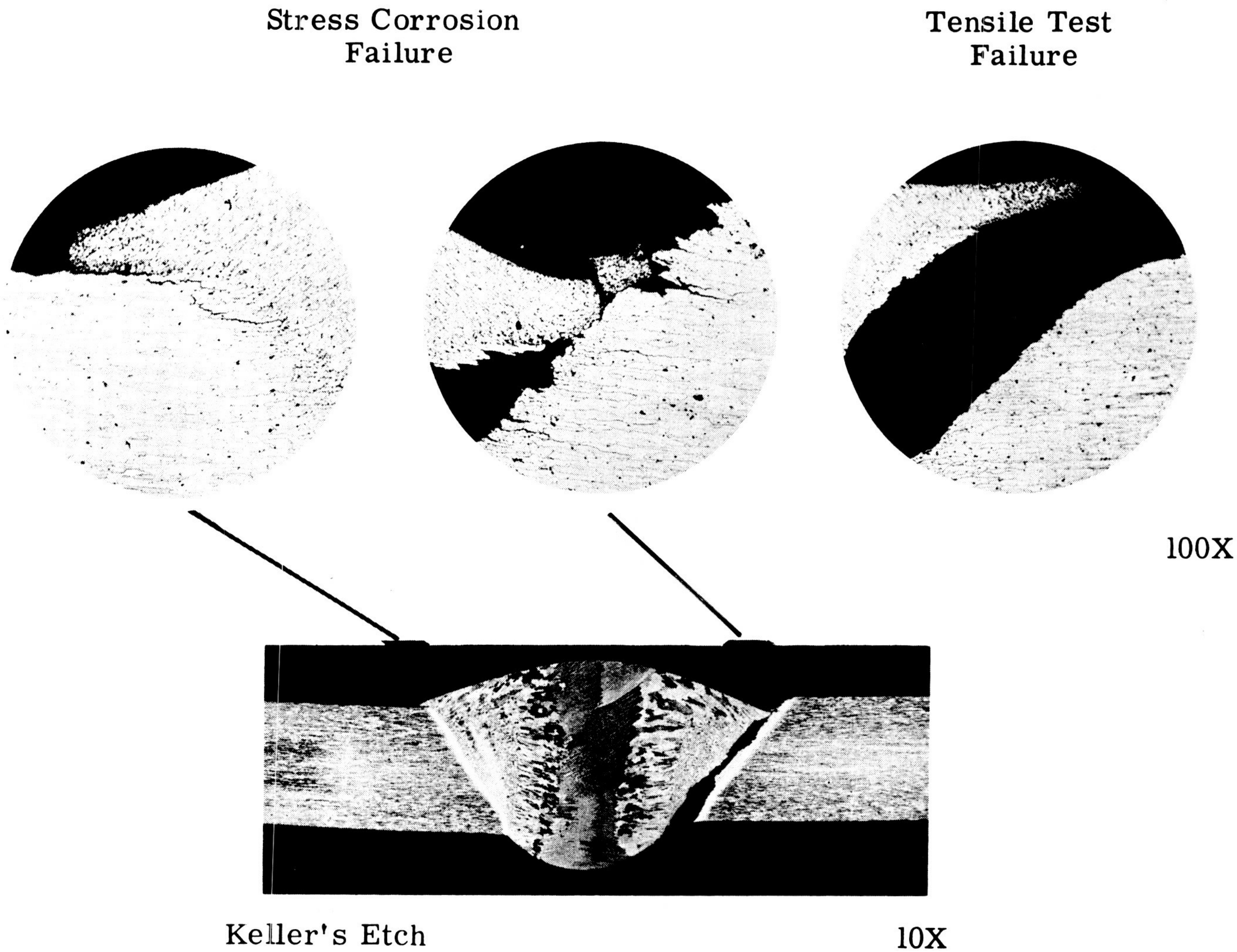


Figure 43 - Representative of failures of TIG welded X7106-T6 and X7139-T6 sheet (1/8" thick) employing X5180 filler wire (post weld aged)

Figure 44a

Neg. No. 144794-A   Mag: 8X   Keller's Etch

S - 320445   X7106-T6351 Plate (Long Transverse)   Left
S - 320426-L   X7106-T6352 Forging (Long Transverse)   Right

Shows the macrostructure of the plate-to-forging combinations. The directionality of the structure of the forging was not as marked as desired for the purpose of this test. Unfortunately there was not a pronounced long or short transverse structure represented.

Figure 44b

Neg. No. 144792-A   Mag: 8X   Keller's Etch

S - 320445   X7106-T6351 Plate (Long Transverse)   Left
S - 320426-S   X7106-T6352 Forging (Short Transverse)   Right

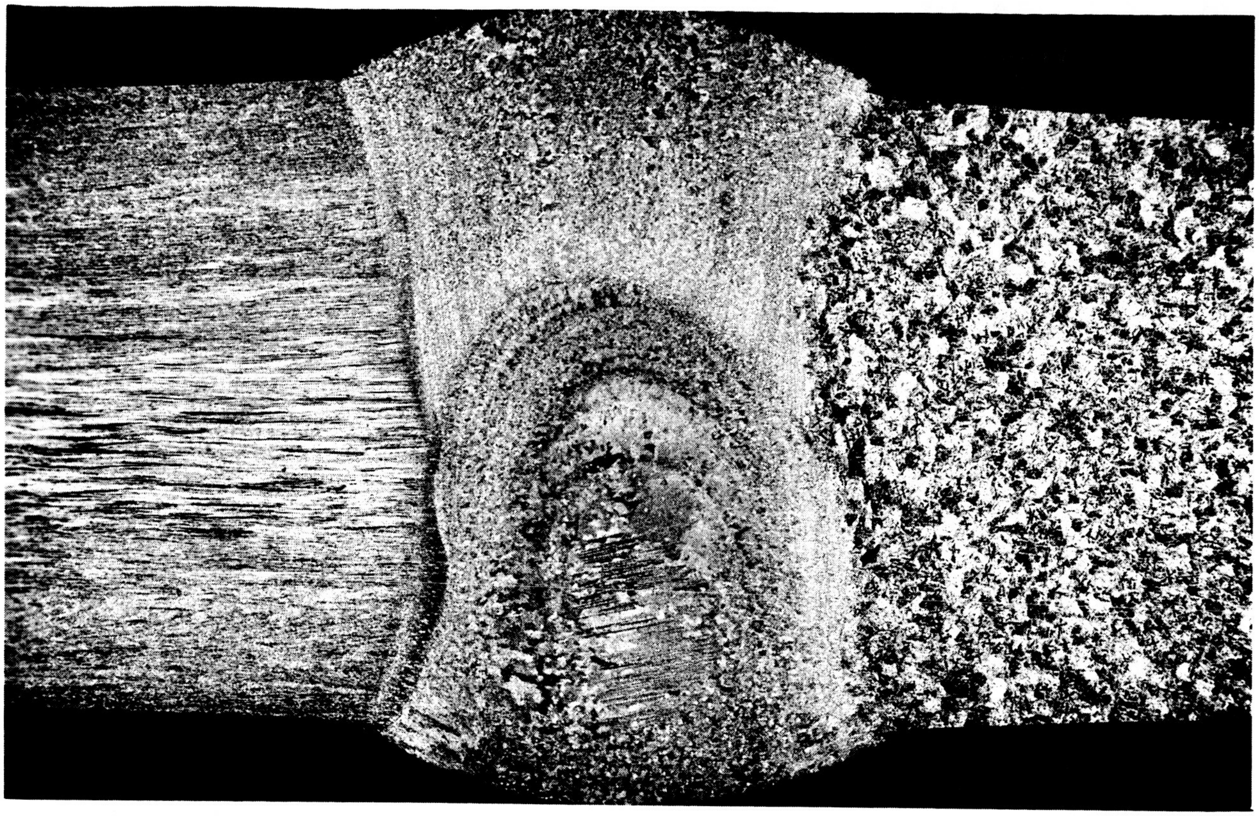


Figure -44a

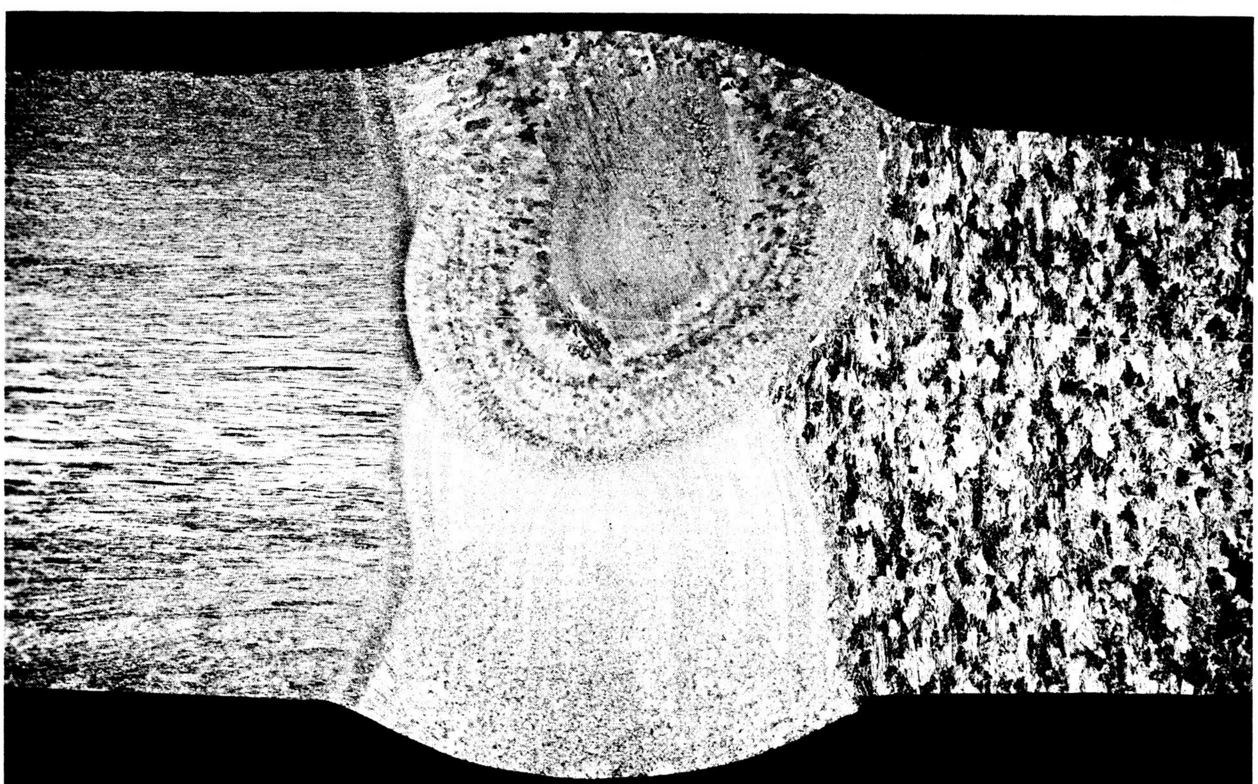


Figure -44b

144794AJ
144792AJ

Figure 45a

Neg. No. 144913-A Mag: 8X Keller's Etch

S - 320445-A1 X7106-T6351 Plate 3/8" Thick

Welded with X5180 and Post Weld Aged

Representative of failure in 3/8" thick weld specimens.

Figure 45b

Neg. No. 144912-A Mag: 3X Keller's Etch

S - 320446-A1 X7106-T6351 Plate 1" Thick

Welded with X5180 and Post Weld Aged

Representative of failures in 1" thick weld specimens.

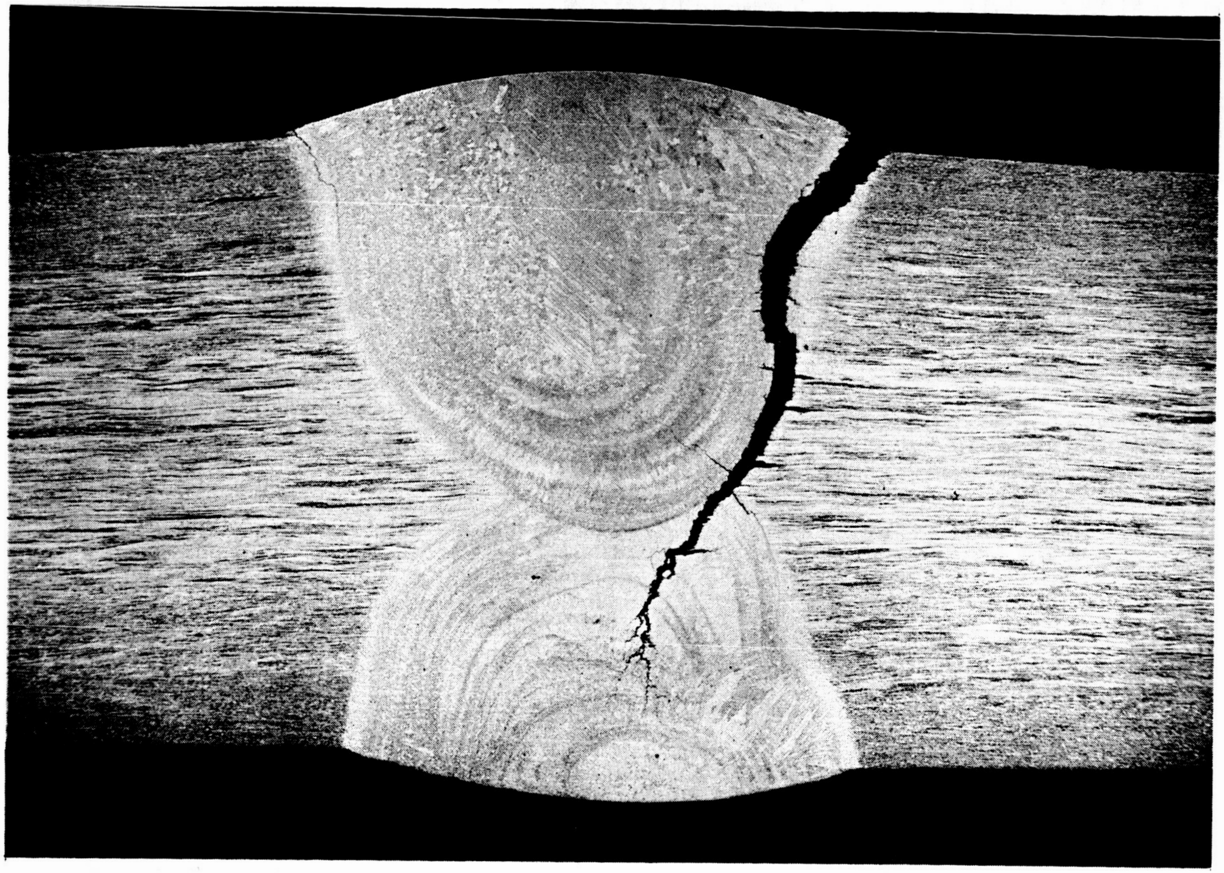


Figure -45a

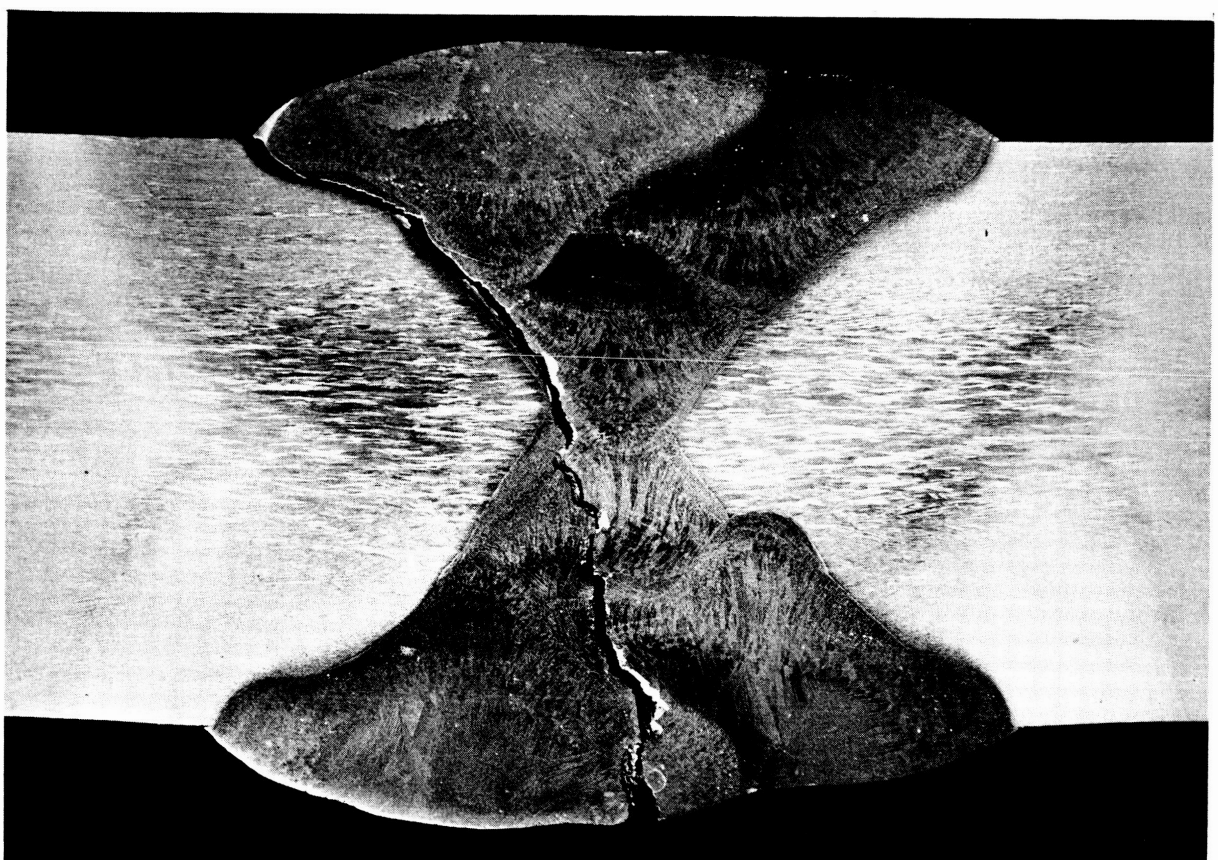
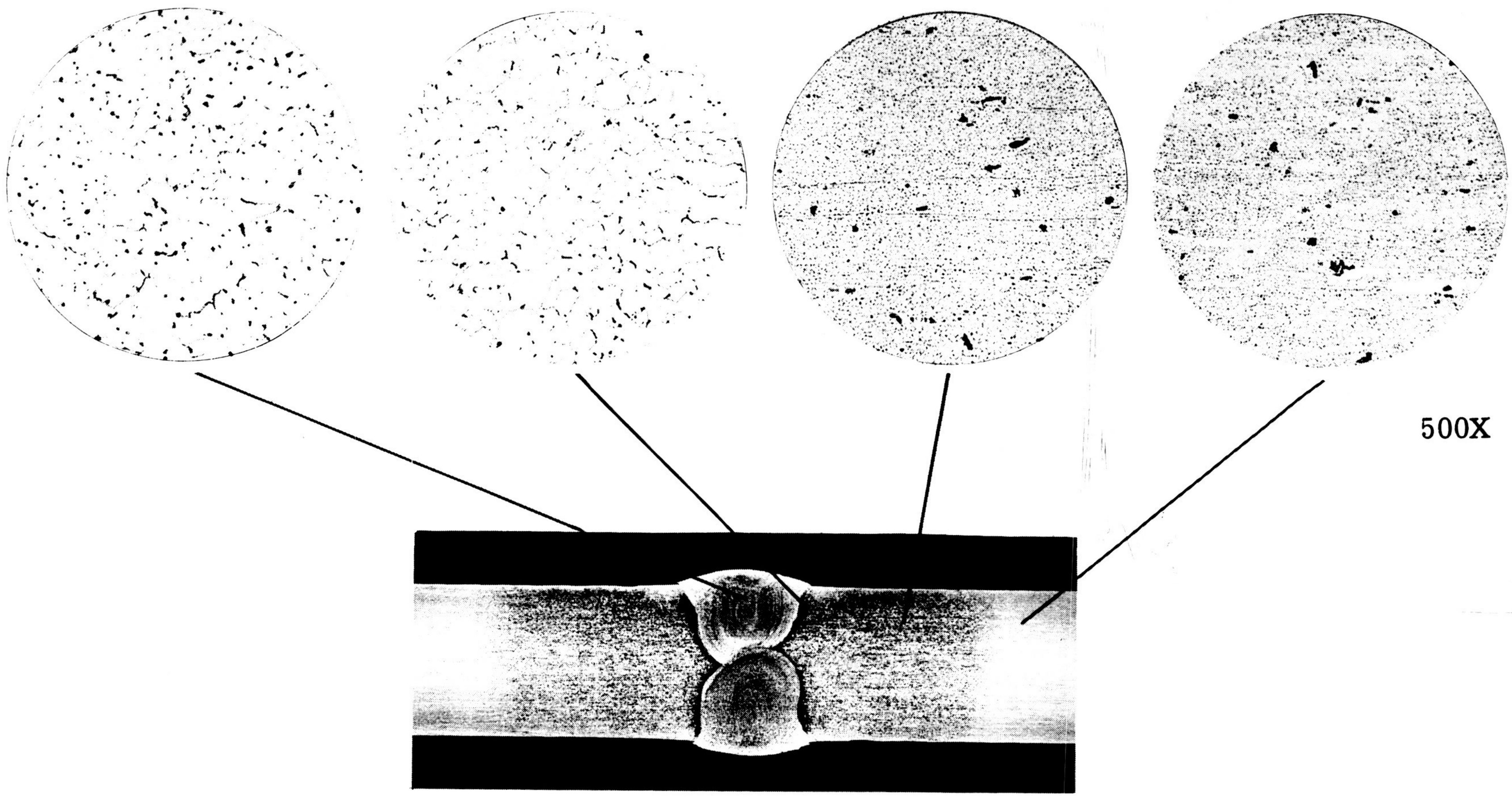


Figure -45b

144913AJ
144912AJ



Keller's Etch 4X

Figure 46 - Microstructures of TIG welded X7106-T6351 3/8" thick plate employing X5180 filler wire

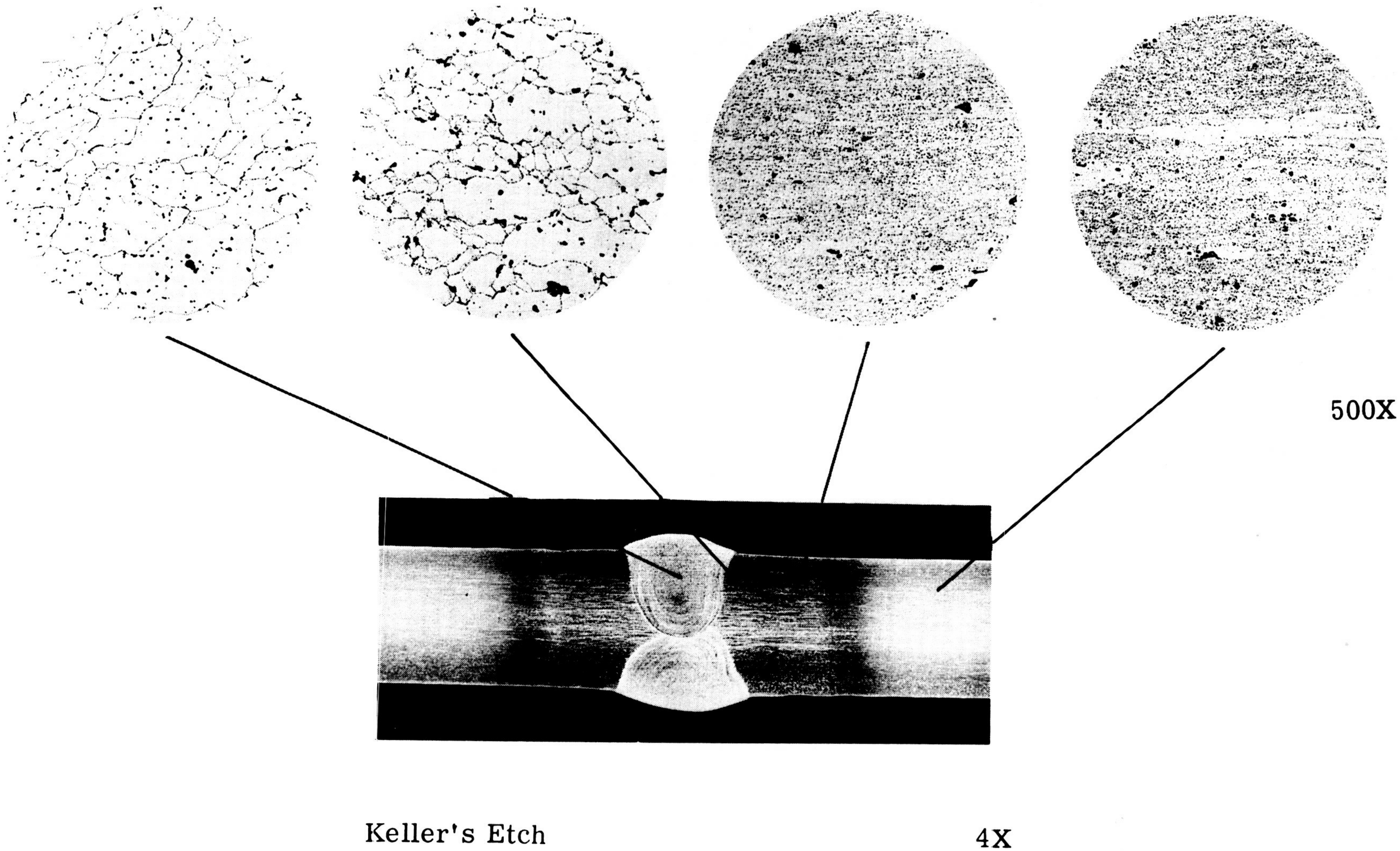


Figure 47 - Microstructures of TIG welded X7106-T6351 3/8" thick plate employing X5180 filler wire (post weld aged 8 hrs. at 225°F + 16 hrs. at 300°F)

S-320445A Mag: 50,000X

Figure 48 - Electron micrograph of the fusion zone penetrated by stress-corrosion cracking of post weld aged X7106-T6351 plate (3/8" thick). Shows the small polygons in the fusion zone, the marked degree of zoning in the matrix, large M-phase precipitate particles on the grain boundary and the zone-free grain boundary paths

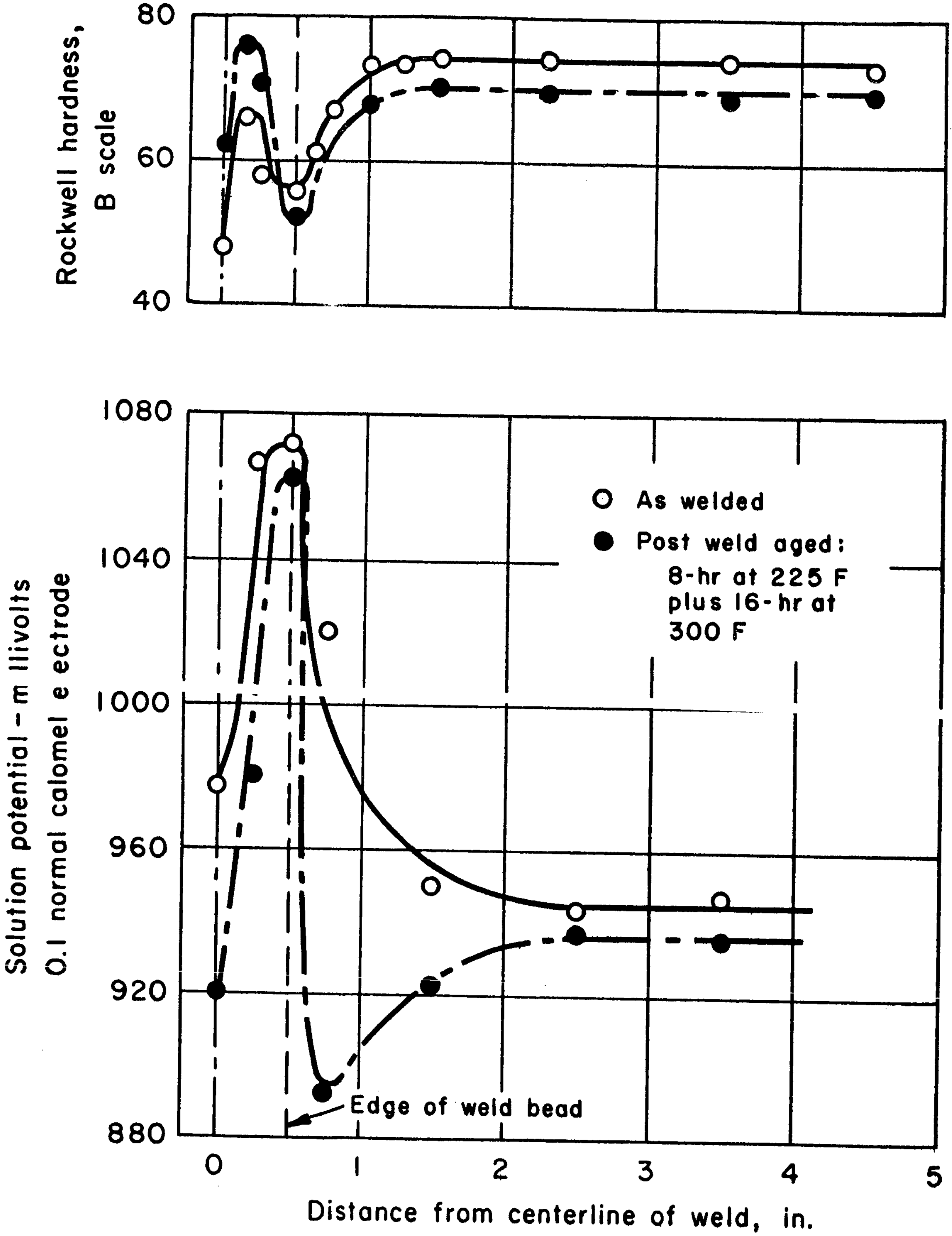


FIG. 49 – HARDNESS AND POTENTIAL MEASUREMENTS ON DCSP-TIG (2-PASS) WELDED 3/8-IN. THICK X7106-T6351 PLATE (X5180 FILLER)

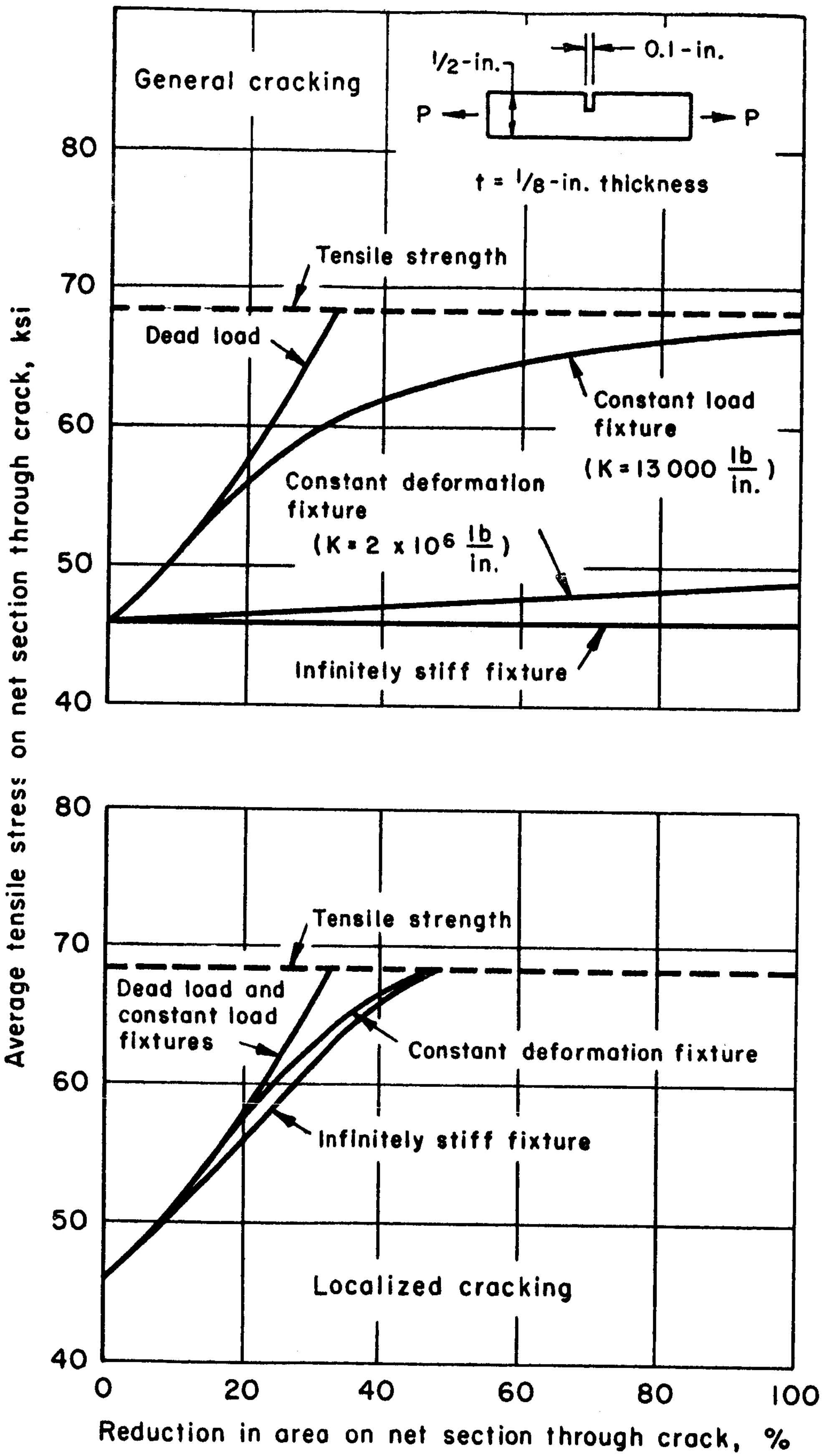


FIG. 50 — EFFECT OF FIXTURE STIFFNESS AND EXTENT OF CRACKING ON AVERAGE NET SECTION STRESS IN SHEET-TYPE TENSION SPECIMENS

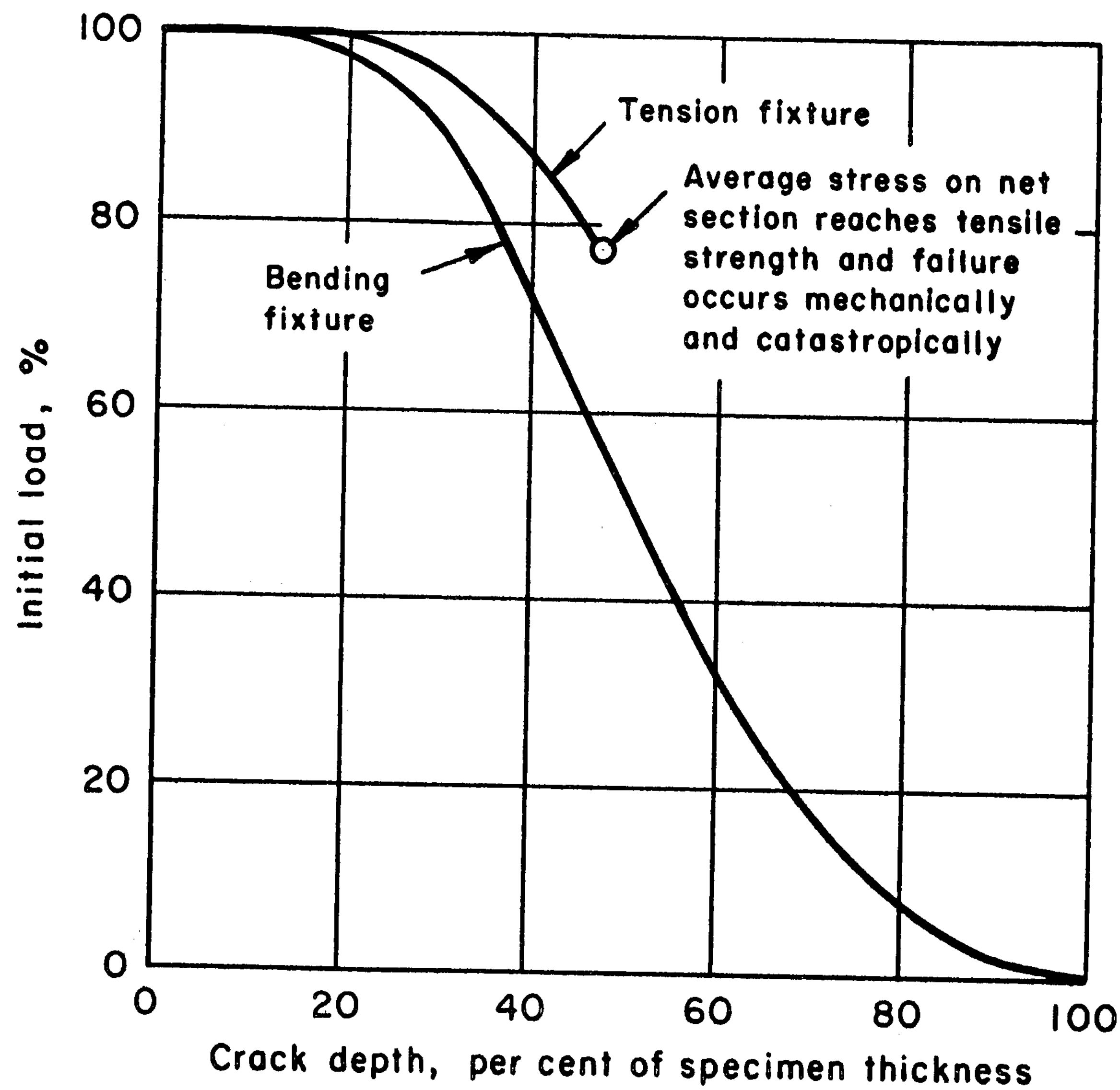


FIG. 51 — COMPARISON OF RELAXATION OF LOAD CAUSED BY LOCALIZED CRACKING OF STRESS-CORROSION SPECIMENS IN CONSTANT DEFORMATION TENSION AND BENDING FIXTURES

APPENDIX C

Technical Data

1. Details of Application of Protective Treatments.
2. Welding Procedure and Equipment Employed in the Preparation of Corrosion Test Specimens of Alloys X7106, X7002, 7039 and X7139.

APPENDIX C-1

Details of Application of Protective Treatments

System No.	System
2	Shot Peen
	a. Peen with S230 shot in a suction feed, air nozzle type cabinet having a 10 rpm work table. The intensity of the treatments was established with Almen "A" strips at an arc height of 0.011" to 0.012". The specimens were mounted at the center of the table and peened in multiple passes using 70 psi air pressure with nozzle distances, nozzle angles and exposure times as shown in the sketches, Figures 1' and 2', given at the end of this appendix.
	b. Remove iron contamination by Alcoa Process R164.
3.	Metallize with 7072 Alloy
	a. Prepare surface by grit blasting with aluminum oxide No. 24TP under 80 pounds pressure.
	b. Heat specimens to approximately 200°F just prior to metallizing.
	c. Metallize with 0.090" diameter 7072 alloy wire in three passes to an average coating thickness of 0.005 to 0.007".
4.	Zinc Electroplate (3 to 4 mil)
	a. Degrease.
	b. Alkaline clean (carbonate-phosphate).
	c. Acid dip - 50% HNO_3 for 30 seconds at room temperature.
	d. Zinc immersion treatment (modified).
	e. Rochelle copper strike.
	f. Zinc plate (either acid or cyanide type solution).

System No.	System
5	Alumilite 205 (0.2 mil) (sulfuric acid anodic) a. Degrease. b. R3 etch. c. Alumilite 205 procedure according to Alumilite Instructions Booklet.
6	Alumilite 226 (2 mil) - Hard Coat Anodic a. Degrease. b. R3 etch. c. Alumilite 226 procedure in accordance with Alcoa Finishes Bulletin No. 14, July, 1960. d. Hard anodic coatings are not recommended for aluminum alloys containing over 5% copper. At present, it is questionable that a suitable hard anodic coating can be produced on 2219 coated by employing a modified Alumilite 226 procedure - using a current density of 24 amp/ft^2 rather than the specified 36 amp/ft^2. The 7000 series alloys can be hard coated satisfactorily.
7 to 12 incl.	Preparation of Surfaces: All Items to be painted except those being painted with the zinc-rich coating should receive a conversion coating of the Alodine 1200 type, per MIL-C-5541. It has been found that heat treat films interfere seriously with the formation of properly adhering chromate conversion films. Although the specimens in this investigation will be machined, some assemblies in practice may have unmachined surfaces. It is believed most secure, therefore, to follow a surface preparation schedule that would be employed if heat treat films were present on unmachined surfaces. This preparation consists of an inhibited alkaline cleaner followed by water rinse, followed by an R3 deoxidizing step, followed by a double water rinse.

System No.	System
7 to 12 incl.	The following will represent the coating schedule through the Alodine coating for items 7 through 12. Step 1. Degrease with inhibited alkaline cleaner. Step 2. Double rinse. Step 3. R3 immersion for heat treat film removal. Step 4. Double rinse. Step 5. Alodine 1200 dip to obtain a 20 to 30 milligram/square foot conversion coating weight. Step 6. Double rinse. Step 7. Force dry conversion coating.
7	Alodine 1200 + Zinc Chromate (Yellow)(1/2 mil) a. Apply zinc chromate (yellow) primer per MIL-P-8585A to a dry film thickness of 1/2 mil. Air dry for 72 hours.
8	Alodine 1200 + Epoxy-Polyamide (2 mil) a. Apply epoxy-polyamide coating per MIL-C-22750A to a dry film thickness of 2 mil. Air dry for 72 hours minimum prior to exposure.
9	Alodine 1200 + Strontium Chromate Epoxy Primer (1 mil) + Epoxy-Polyamide (2 mil). a. Apply strontium chromate epoxy primer per MIL-P-23377 to a dry film thickness of 1 mil. Air dry for 72 hours. b. Apply epoxy-polyamide coating per MIL-C-22750a to a dry film thickness of 2 mil. Air dry for 72 hours minimum prior to exposure.

System No.	System
10	Alodine 1200 + Strontium Chromate Epoxy Primer (1 mil) + Epoxy-Polyamide Vehicle with Added Aluminum Pigment (1 mil) + Epoxy-Polyamide (2 mil) a. Apply strontium chromate epoxy primer per MIL-P-23377 to a dry film thickness of 1 mil. Air dry for 72 hours. b. Apply an intermediate coating consisting of an epoxy-polyamide vehicle identical to that used in MIL-22750a to which aluminum pigment, Alcoa 221, is added at rate of 2.5 pounds per gallon of vehicle 50% resin content, to a dry film thickness of 1 mil. Air dry for 72 hours. c. Apply epoxy-polyamide per MIL-C-22750A to a dry film thickness of 2 mil. Air dry for 72 hours minimum prior to exposure.
11	Alodine 1200 + Polyurethane Pigmented with Titanium Dioxide (2 mil) a. Apply a polyurethane coating pigmented with titanium dioxide to a dry film thickness of 2 mil. Air dry for 72 hours minimum prior to exposure. This paint is not covered by a military or federal specification. The best commercial material will be used.
12	Alodine 1200 + Strontium Chromate Epoxy Primer (1 mil) + Polyurethane Pigmented with Titanium Dioxide (2 mil) a. Apply strontium chromate epoxy primer per MIL-P-23377 to a dry film thickness of 1 mil. Air dry 72 hours. b. Apply a polyurethane coating pigmented with titanium dioxide to a dry film thickness of 2 mil. Air dry for 72 hours minimum prior to exposure.

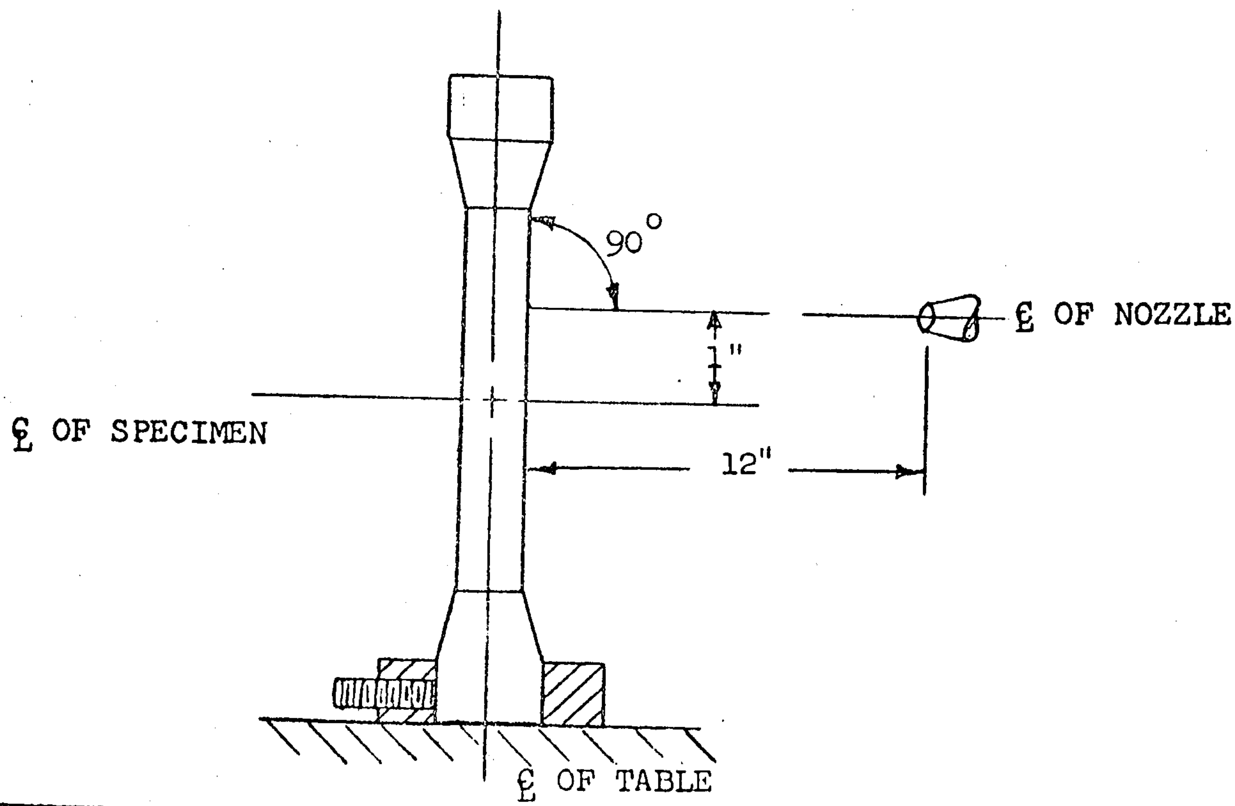
System No.	System
13	Zinc-Rich Paint (Epoxy-Polyamide Pigmented with Zinc) (3 mil)
	a. Degrease with inhibited alkaline cleaner.
	b. Double rinse.
	c. Apply a zinc-rich paint comprised of an epoxy-polyamide coating pigmented with atomized zinc at a rate of 50 to 60 per cent pigment volume concentration, to a dry film thickness of 3 mil. Air dry for 72 hours, minimum prior to exposure.
14	Shot Peen + Alodine 1200 + Strontium Chromate Epoxy Primer (1 mil) + Epoxy-Polyamide (2 mil)
	a. Shot peen and clean as in System 2.
	b. Alodine 1200.
	c. Apply strontium chromate epoxy primer per MIL-P-23377 to a dry film thickness of 1 mil. Air dry 72 hours.
	d. Apply epoxy-polyamide coating per MIL-C-22750A to a dry film thickness of 2 mil. Air dry for 72 hours minimum prior to exposure.
15	Metallize with 7072 Alloy (5 to 7 mil) + Alodine 1200 + Strontium Chromate Epoxy Primer (1 mil) + Epoxy-Polyamide (2 mil)
	a. Metallize as in System 3.
	b. Alodine 1200.
	c. Apply strontium chromate epoxy primer per MIL-P-23377 to a dry film thickness of 1 mil. Air dry 72 hours.
	d. Apply epoxy-polyamide coating per MIL-C-22750A to a dry film thickness of 2 mil. Air dry for 72 hours minimum prior to exposure.

NAS-8-5340 CONTRACT - PEENING TREATMENT
FOR TENSILE SPECIMENS

ALMEN "A" INTENSITY OF .011" TO .012" USING S230 SHOT AT 70 PSI AND 10 RPM TABLE SPEED

(A) 1"

(B) NOZZLE DISTANCE = 12"
NOZZLE ANGLE = 90°



PASS NO. 1 - A 2-1/2 MINUTE EXPOSURE WAS MADE AS SHOWN ABOVE.

PASS NO. 2 - THE SPECIMEN WAS MOUNTED AT THE OPPOSITE END AND WAS AGAIN PEENED FOR 2-1/2 MINUTES USING THE SAME NOZZLE POSITION.

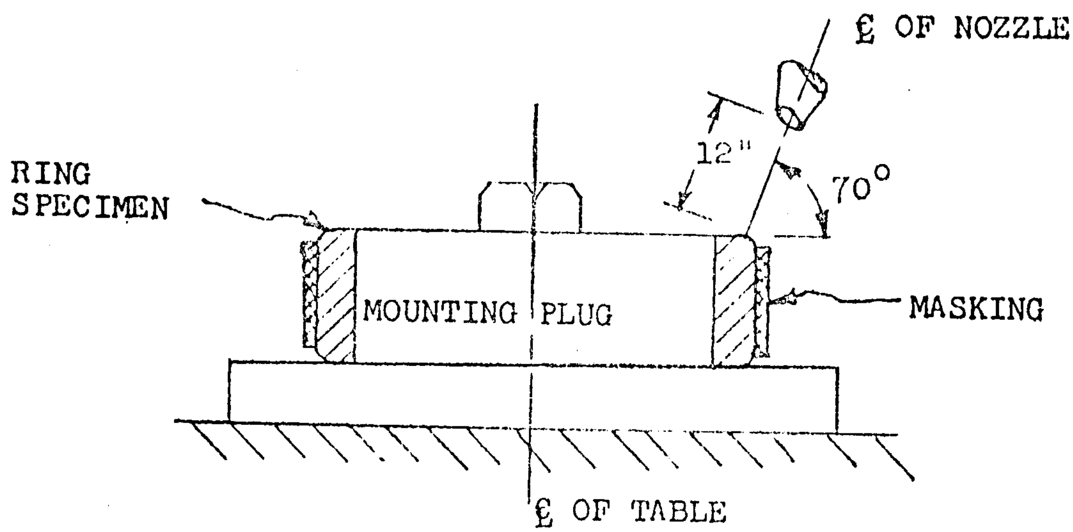
Figure 1

NAS-8-5340 CONTRACT - PEENING TREATMENT FOR RING SPECIMENS

ALMEN "A" INTENSITY OF .011" TO .012" USING S230 SHOT AT 70 PSI AND A 10 RPM TABLE SPEED

PASS NO. 1 - EXPOSURE TIME = 5 MINUTES.

NOZZLE DISTANCE = 12"
NOZZLE ANGLE = 70°



PASS NO. 2 - SAME AS NO. 1 - ON OPPOSITE EDGE OF RING.

PASS NO. 3 - EXPOSURE TIME = 3 MINUTES.

NOZZLE DISTANCE = 12"
NOZZLE ANGLE = 90°

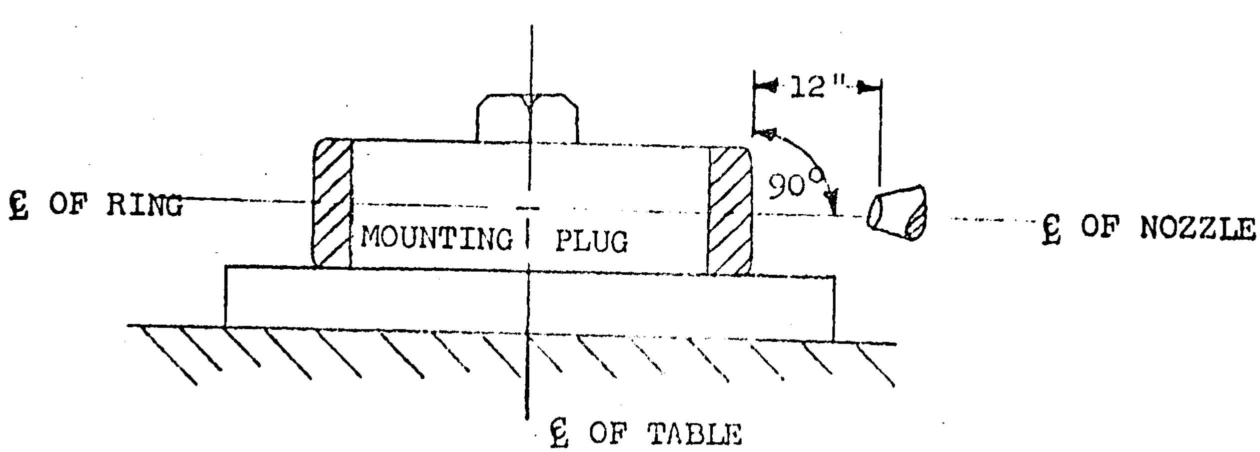


Figure 2

APPENDIX C-2

WELDING PROCEDURE AND EQUIPMENT EMPLOYED IN THE PREPARATION OF CORROSION TEST SPECIMENS OF ALLOYS X7106, X7002, 7039 AND X7139

Welding Procedure:

	Stress Corrosion Test Panels			
	1/8" Thick (DCSP-TIG)(1)	3/8" Thick (DCSP-TIG)	3/8" Thick (DCRP-MIG)(2)	1.0" Thick (DCRP-MIG)(2)
Current (Amps.)	235-265	310-330	280-290	300-320
Volts	12	13-14	24-26	31-34
Wire Feed	48 ipm	32 ipm	320 ipm	370 ipm
Shielding Gas	70 cfh HE	70 cfh HE	60 cfh AR	40 cfh HE; 20 cfh AR
Travel Speed	20 ipm	10-11 ipm	30 ipm 1st pass; 20 ipm 2nd pass	10 ipm 1st pass; 11 ipm 2nd pass; 14 ipm 3rd pass
Cup		#10	#11 - 5/8" from work distance	#10 - 1/2" to 5/8" from work distance
Cleaning	caustic-nitric, abutted edges draw filed	vapor degreased-caustic-nitric	vapor degreased-caustic-nitric	vapor degreased-caustic-nitric
Back-up	copper - 1/16" rod x 1/36" deep	steel - 3/8" wide x 3/64" deep	none	1/2" diameter steel rod
Hold Down Pressure		70 psi	70 psi	70 psi
Joint Type	square butt	square butt - dry machine	30° db'l. "V" - 1/16" land - dry machine	45° db'l. "V" - 1/16" land - dry machine
No. of Passes	1	2-opposite direction - no back chip	2-opposite direction - back chip	6-3 each side in opposite direction - back chipped
Lead Angle			5° forward	none

	Stress Corrosion H Plates (4)			
	1/8" Thick (DCSP-TIG)	3/8" Thick (DCSP-TIG)(2)	3/8" Thick (DCRP-MIG)	1.0" Thick (DCRP-MIG)
Current (Amps.)	235-265	280-290	280-290	270-285
Volts	12	12-13	27-39	31-37
Wire Feed	48 ipm	28 ipm	340 ipm	340 ipm
Shielding Gas	70 cfh HE	70 cfh HE	60 cfh AR	40 cfh HE; 20 cfh AR
Travel Speed	20 ipm	11 ipm	32-34 ipm	20 ipm 1st pass; 14 ipm each succeeding pass
Cup		#10 (5/8" I.D.)	#10 - 1/2" to 5/8" from work distance	#10 - 1/2" to 5/8" from work distance
Cleaning	wire brushed	wire brushed	wire brushed	wire brushed
Back-up	none	none	none	none
Hold Down Pressure	none	none	none	none
Joint Type	bead on plate	bead on plate	30° db'l. "V" - 1/16" land - dry machine - no cut	45° db'l. "V" - 1/16" land - dry machine - no cut
No. of Passes	2-opposite direction - no back chip	2-opposite direction - no back chip	2-opposite direction - no back chip	6-3 each side in opposite direction - no back chip
Lead Angle	none	none	none	none

Welding Equipment:

(1) Westinghouse D.C. Arc Power Supply - Type WS, 500 amp, rectifier type.
(2) General Electric Pneumatic Hold-Down.
(3) Alcoa automatic welding unit with CM-37 carriage, G.E. Thy-Mo-Trol control panel, SEH-2 welding head and DM-2420-1 water cooled machine welding torch.

Notes:
(1) Tungsten electrode (1/8" diameter - 2% thorium).
(2) 0.081 I.D. x 2 1/4" long copper guide tube employed.
(3) Tungsten electrode (1/8" diameter - zirconium) protrusion 7/16" to 1/2" below cup.
(4) "H" plates were chilled in dry ice overnight. Weld area heated with oxyacetylene torch to 200°F before welding.

APPENDIX D

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